Australian Government
Department of Defence
Defence Science and Technology Organisation

# A System-of-Systems Engineering Approach for Australian Land Force Capability Integration

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DSTO-TR-2743

**ABSTRACT**

A system-of-systems engineering approach to suit the Australian land force capability integration challenge is developed drawing on the international body of knowledge. The approach proposed would require only quite modest resources. The nature of the activities and the artefacts to produce are defined, with a focus on SoS requirements engineering aspects and how these influence the resulting project- and SoS-level test and evaluation activities.

*Published by*

*Land Operations Division*
*DSTO Defence Science and Technology Organisation*
*PO Box 1500*
*Edinburgh South Australia 5111 Australia*

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*AR-015-388*
*September 2012*

**APPROVED FOR PUBLIC RELEASE**

# A System-of-Systems Engineering Approach for Australian Land Force Capability Integration

## Executive Summary

This report forms the final report of a Research Agreement between Land Operations Division of DSTO and the Defence Systems Innovation Centre (DSIC) entitled *Research Project for SoS Requirements and Evaluation.* It builds on the outline of an overarching Systems of Systems Engineering (SoSE) approach for land force capability engineering described in Deliverable 1 (Cook and Nowakowski, 2012) and the success factors for Systems of Systems (SoS) programs enumerated in Deliverable 3 (Cook, et al., 2012).

The report opens with a description of the broad land force capability challenge and then focuses on the central issues to be examined in this report, namely the provision of advice on how best to achieve:

1. Capability/SoS project requirements development and specification; and

2. Test and Evaluation (T&E) processes for capability/SoS integration to ensure that the delivered constituent systems will be effective components of land force capability.

Specifically, it was agreed that the requirements engineering and test and evaluation advice sought would need to be framed within the context of a defined land force capability integration approach and hence the body of the report commences by defining the elements of capability needed to undertake Army SoS integration for the tactical land force operating in a joint environment. These are: overarching principles and approach; organisation, roles and responsibilities; SoS engineering environment; personnel; training; SoS design and synthesis; and SoS test and evaluation. Success factors for each element of SoSE capability are described next to inform the design and implementation of a SoSE approach for the land force.

SoS capabilities can be implemented in different ways informed by equally different frameworks of ideas. A description of the five leading schools of thought on SoSE follows to provide an understanding of the diversity of approaches that are gaining traction around the world. The starting school of thought chosen for the land force capability integration challenge was the US Department of Defense (DoD) SoSE approach because it is the most mature in many respects, is well documented, is well-known and respected in Australia (indeed it acknowledges Australian input), and is a defence methodology and hence well-

suited to the problem at hand. The US DoD approach, however, has been developed to suit rather different resource levels, contractual arrangements, and governance models. The argument is then made that it is necessary to tailor the US approach to suit Australia's level of SoSE capability maturity, cultural differences, and prospective level of SoSE funding and a set of guiding principles for the design of the Australian approach is then described based on the literature, the authors' knowledge of the Australian defence enterprise, and a review of the success factors. The point is made that SoSE is yet to commence in earnest in Australia and, as such, the focus in the first one or two iterations will need to be on 'herding' the projects to achieve SoS outcomes and then to progressively adopt the precepts of capability engineering to shape the project requirements.

The design of an Australian land force capability SoS approach is described in Section 4 by suggesting how the five US DoD SoSE lifecycle stages can be adapted. Included in this description are the outputs of each of the phases embodied in the form of artefacts that would need to be produced during each iteration. An Australianised description of the artefacts can be found in Annex B.

A key message arising from the research that underpins the findings of this report is that SoSE is an enterprise-level activity that relies on stakeholder buy-in and commitment to achieve success. Success always depends on the stakeholder perspective and, after the SoS Team, the most important perspective to consider is that of the constituent system System Project Offices (SPOs). The analysis of the SoSE activity from this perspective readily surfaces the need to incentivise SPOs to develop their products and services in such a way as to maximise SoS outcomes. A description of the Land SoSE support environment completes the description of the proposed Australian SoSE approach.

Section 5 addresses the first question explicitly. We show how capability requirements for the SoS are elicited and how the SoSE analysis stage identifies how these can be mapped onto constituent systems in the form of high-level service definitions (analogous to service contracts). In the first iteration, the SoS Team will have little opportunity in the short term to change constituent systems requirements or project scope and hence the approach chosen to interface to the SPOs is to establish agreements that embody the service definitions. It is these service and interface definitions that are tracked by both parties and form the basis for guiding the evolution of the SoS.

Section 6 addressed the second question explicitly. Firstly, SoS T&E is fundamentally different in goals, character, and intent from system-acquisition T&E that seeks to inform acceptance and deployment decisions. SoS T&E is focussed more on SoS verification and validation because it is deemed impractical to conduct comprehensive testing of an evolving SoS. Thus SoS T&E activities focus on the impacts that iterations of constituent systems will make on the SoS performance and behaviour outcomes. As such, it involves far greater use of modelling, simulation and analysis than project T&E and thinking of training, exercises, and operations as T&E opportunities. Nonetheless, the SoS T&E staff would monitor the constituent system project progress to evaluate whether the service provision clauses of the agreements will be achieved.

SoSE metrics are beginning to develop. These would become useful when the Australian managerial and technical processes become established. We suggest that a metric-based approach is inappropriate during the initial iterations of SoSE because it would encourage counterproductive stakeholder behaviour, and is covered in Section 7.

In summary, this report draws on the international body of knowledge to develop a SoSE approach to suit the Australian land force capability integration challenge. It uses the US DoD approach for its outline supplemented by social and cultural aspects from European and civilian experiences. The approach proposed would require quite modest resources, "a few top people", supported by contemporary tools, and some modest additional funding for constituent system SPOs. The nature of the activities and the artefacts to produce are defined. Specific attention has been paid to SoS requirements engineering aspects and how these influence the resulting project- and SoS-level T&E activities. A final point is that SoSE is quite different from project SE and SoS T&E is fundamentally different from project-based T&E. Both disciplines will require highly-capable and adaptable people that display the appropriate mind-set needed for SoS success. Identifying and nurturing the development of these people is an important subject for further consideration.

Ultimately, the success of SoSE will be judged in terms of the achieved SoS capability performance versus the cost of undertaking SoSE. A key return on investment for SoSE is likely to be a transfer of the SoS integration risks from the operational level (i.e. the warfighters), where they have been traditionally addressed, to the capability development domain.

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# Glossary

| | |
|---|---|
| ACAT | Acquisition Category |
| ASN (RD&A) | Assistant Secretary of the Navy (ASN) (Research, Development & Acquisition) |
| BOS | Battlefield Operating System |
| C4I | Command, Control, Communications, Computers, Intelligence |
| C4ISREW | Command, Control, Communications, Computers, Intelligence, Surveillance, Reconnaissance and Electronic Warfare |
| COI | Communities of interest |
| CONOPS | Concept of Operations |
| COTS | Commercial off the Shelf |
| DISC | Defence Systems Innovation Centre |
| DoD | Department of Defence |
| DOTMILPF | Doctrine, Organisation, Training, Material, Leadership and Education, Personnel and Facilities (US) |
| DSTO | Defence Science and Technology Organisation |
| DT | Developmental Test |
| ESE | Enterprise Systems Engineering |
| FAA | Federal Aviation Administration |
| FIC | Fundamental Inputs to Capability: Organisation, Personnel, Collective Training, Supplies, Facilities, Major Systems, Support, Command & Management (Australia) |
| FPS | Functional Performance Specification |
| HESI | High End Systems Integration |
| IMS | Integrated Master Schedule |
| INCOSE | International Council on Systems Engineering |
| IPT | Integrated Project Team |
| ISR | Intelligence, Surveillance and Reconnaissance |
| JCIDS | Joint Capabilities Integration and Development System |
| JSA | Joint Systems Analysis |
| LCVS | Land Combat Vehicle System |
| MBSE | Model based Systems Engineering |
| MCE | Major Capital Equipment |
| MOTS | Military off the Shelf |
| NCW | Network Centric Warfare |
| NCWIIS | NCW Integration and Implementation Strategy |
| NDIA | National Defense Industrial Association |
| OCD | Operational Concept Document |
| OSD | Office of the Deputy Under Secretary of Defense |
| OT | Operational Test |
| OT&E | Operational Test and Evaluation |
| PMSG | Program Management Steering Group |
| PRICIE | Personnel, Research & Development, Infrastructure, Concepts & Doctrine, Information Technology, Equipment (Canada) |
| QL | Quick Look |

| | |
|---|---|
| R&D | Research and Development |
| RPDE | Rapid Prototyping, Development and Evaluation |
| SE | Systems Engineering |
| SEI CMMI | Software Engineering Institute Capability Maturity Model Integration |
| SEP | Systems Engineering Plan |
| SoS | System-of-Systems |
| SoSE | System-of-Systems Engineering |
| SoSI | SoS integration |
| SPO | System Program Office |
| SysML | Systems Modeling Language |
| T&E | Test and Evaluation |
| TSE | Traditional Systems Engineering |
| TTCP | The Technical Cooperation Program |
| USAF | United States Air Force |
| USN | United States Navy |
| WSAF | Whole-Systems Analytical Framework |

# 1. Introduction

## 1.1 Background

In the Land domain, systems integration presents a major challenge to delivering effective and survivable war fighting capability ranging from force level joint and combined arms teams, through close combat teams, down to the individual soldier. This is driven by a number of factors including: the inherent complexity of operations; rapidly increasing complexity of the soldier; vehicles and other systems; and the Defence preference for commercial off-the-shelf (COTS) or military off-the-shelf (MOTS) acquisition. It has, therefore, become essential to better align many elements of Defence and industry to deliver effectively integrated systems and capabilities to the soldier and commanders.

Land force capability is generally acquired within individual projects (both major and minor) that will deliver specific systems. These systems will not necessarily be optimised to integrate into wider land forces. Thus, there is a need to more clearly understand what is required to achieve land force capability integration and how individual projects can specify and evaluate systems such that they will be able to effectively integrate into the broader land force capability or system-of-systems (SoS).

## 1.2 Scope

This report is one of three reports that are the culmination of a joint research program between the Defence Systems Innovation Centre (DISC) and DSTO on the challenge of land force integration (CAPO 2011). The first (Cook and Nowakowski, 2012) provides an initial outline of an overarching approach to address the problem. The second (Cook et al., 2012) identifies and analyses the lessons learned in implementing SoS. This report builds on these two reports to deliver advice on (CAPO 2011):

1. Capability/SoS project requirements development and specification; and

2. Test and Evaluation (T&E) process for capability/SoS integration to ensure that the delivered constituent systems will be effective components of land force capability.

The interpretation of the intent and content of this deliverable was honed during the conduct of the research task in a sequence of project meetings. It was agreed that the requirements engineering and test and evaluation advice sought would need to be framed within the context of land force capability integration, and hence significant effort was devoted to outlining a viable SoS integration (SoSI) approach for the tactical land force operating in a joint environment. We used battalion-level and amphibious operations to frame our thinking.

Furthermore, the scope was clarified to include the requirements and T&E at both the land force level and the constituent project level.

# 2. The Land Force SoSI Challenge

Recent studies have indicated that the biggest systems integration challenge facing the Australian Defence Organisation is systems-of-systems integration (sometimes referred to as cross-project integration) (RPDE, 2011; Defence, 2012). System of Systems Integration (SoSI) refers to the integration of interoperable communication, command and control, and support systems between various platforms which link, for example, the Landing Helicopter Dock with air support, amphibious watercraft, support ships, and land forces, in order to provide the overarching amphibious capability. SoSI is a key capability for realising the Networked Force described in the 2009 Defence White Paper: Defending Australia in the Asia Pacific Century: Force 2030 and in ancillary documents such as the NCW Roadmap and the ISR Roadmap.

SoSI is achieved through the application of systems engineering tailored to reflect the SoS context: there usually is no single owner of a SoS, and independent, concurrent management and funding at both the constituent system level and at the SoS level is the norm (Maier, 1998; Chen and Clothier, 2003; Valerdi et al 2008, OSD 2008). Hence, to achieve effective SoSI, it becomes necessary for key players to influence other parties (in particular independent SPOs) on the basis of perspective, breadth of knowledge, and analysis, rather than from a position of authority (Oxenham and Swales, 2010). The discipline that tackles SoSI is internationally known as SoS Engineering (SoSE) but it is still in its infancy and SoSE remains a challenge throughout the world.

This report is informed by a substantial literature review, the work of The Technical Co-operation Program panel TTCP-JSA-TP4: Systems Engineering for Defence Modernisation, and several recent studies in the defence SoS field. Of particular relevance to the design and evolution of a Land SoSE capability is the description of SoSE Success Factors that can be found in Cook et al. (2012) that builds on a substantial literature base and recent Australian studies (RPDE, 2011; Defence, 2012). Interested readers are referred to Annex A for comprehensive definitions of the terms such as SE, SoS, SoSI and SoSE.

# 3. A Capability-based Approach to SoS Engineering

The ability to undertake SoSE can usefully be thought of as a capability that, like a military capability, requires the synthesis of many components to realise the desired effect; indeed Sage and Cuppan (2001), among others, assert that there is value in thinking of the social system that undertakes SoSE as a complex adaptive system and using this stance to inform its definition and evolution. There are many variations of the definitions of the elements of military capability: Fundamental Inputs to Capability (Defence 2011), PRICIE (Hendry 2007), Defence Lines of Development (MOD 2009), and DOTMLPF (Defence 2009a). These have been synthesised as shown in Figure 1 to arrive at a list of capability elements for SoSE capability. These elements need not be thought of as strictly orthogonal, rather they can be considered to be perspectival views of SoSE enterprise. The figure also draws on ANSI/EIA-632 to indicate that SoSE, just like project engineering, operates within an environment that sets the external and enterprise context for SoSE planning and conduct of the activities. The external environment covers laws and regulations, legal liabilities, social responsibility, technology base, labour pool, competing products, standards and specifications, and public culture. For the case in hand, the enterprise environment covers Defence policies and procedures, standards and specifications, guidelines, domain (Land and military information system technologies, and local culture. The conduct SoSE will also be shaped by environmental factors that will apply specifically to the SoS, for example directives and procedures, plans, tools, reviews and metrics.

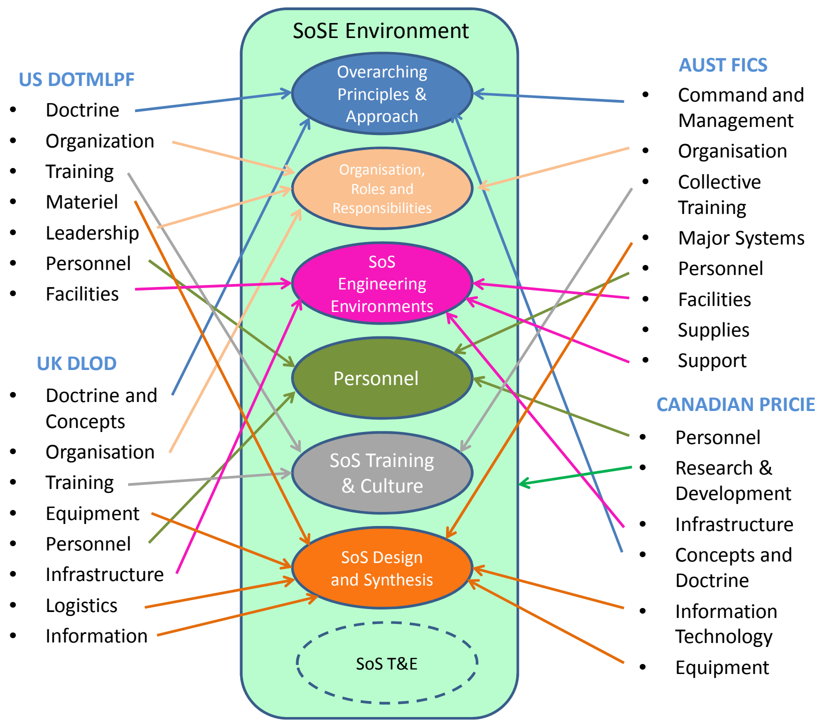



*Figure 1. The derivation of the elements of SoSE capability*

A brief discussion on each of these elements of SoSE capability follows along with some of the constraints in which they need to operate in the Australian capability development environment. Also included in each element is a list of success factors of relevance to the land force capability SoS we are considering.

## 3.1 Australian SoSE Environment

Figure 2 illustrates the key environmental factors that influence the selection and implementation of any Australian Defence SoSE approach. The Australian Defence Enterprise Environment includes the capability of the Australian Defence Systems Engineering and Integration Enterprise (this includes all the contributors from government, contractors, and academia) as well as the technology base, public culture, the legal and contractual framework and norms, government policies such as the Defence Industry Policy, and the nature and volume of the work that is in progress and programmed into the Defence Capability Plan.

We also know that the decision on the SoSE approach to use would need to be informed by government and defence directives and policies, coalition and national operational needs, the current and future Land Defence Outputs, and the international literature on SoSE, in particular the guidebooks and practices.

The finding of Unewisse and Cook (2011a & b) coupled with more investigations (Defence, 2012) indicate that the Australian Defence Enterprise has modest capability in SoSE and, as such, it is fair to say that any approach initiated in this environment could expect to exhibit a low capability maturity level and would rely on "heroes" and "wise heads" rather than process to achieve its objectives (Sage and Cuppan, 2001).


*Figure 2. A context diagram for the Australian Land SoSE approach*

## 3.2 Discussion on Overarching Principles and Approach

The Overarching Principles and Approach includes the SoS design, management and coordination approach, the definition of requirements for the other elements, particularly the engineering and validation environments, and key business processes and procedures. The latter define what SoSE will comprise and how it will be planned, applied, monitored, and evaluated.

Of the guidebooks, the most referenced body of knowledge with respect to military SoS integration is the US Department of Defense's Systems Engineering Guide for Systems of Systems (OSD, 2008) that is based on the study of 18 SoSs. It provides the following insights:

- SoSE management is essentially different from, and more complex than, single-project management because there is limited authority to influence the SPOs providing the constituent systems.
- SoSE will never be a "one-size-fits-all" process but rather something that must be developed and tailored in cognisance of key SoS constituent systems and their lifecycles.
- SoSE requires an emphasis on end-to-end performance and behaviour management to ensure that the ensemble of systems will meet capability targets.

The guide identifies Principal SoSE Elements, SoSE Principles, and Focus Areas for SoSE Management and these, coupled with later work on the "Wave Model" of SoSE (Dahmann et al, 2011), form a useful starting place for the identification of an overall Australian Land SoSE approach.

This element will also surface and promulgate the principles that will inform SoSE practice. Some example principles are listed below that are adapted from the US SoSE Guide (OSD, 2008):

- SoSE can only commence when a SoS has been acknowledged, roles and responsibilities have been defined, and resources have been allocated to the task.
- It is essential to focus on the design strategy and trades both when the formal SoS is first established and throughout the SoS evolution.
- Organizational as well as technical issues need to be addressed in making SE trades and decisions.
- The different roles of systems engineers at the system, versus the SoS, level and the relationship between the SE done at the two levels, must be acknowledged.
- Success depends on the ability of SoS managers to work across systems and balance technical and non-technical issues. This requires experienced, capable SoS managers and SE teams.
- Use a SoS solution based on open systems techniques and loose coupling.
- Knowledge management is a vital enabler for effective SoSE.

Just as the definitions of the elements of capability differ in Australia from allied countries so will the definition of the principles that will need to inform our SoSE practice. Thus the above should be seen as an example from which we can evolve the final set.

It should be recognised that SoSE usually commences after the constituent systems are in service, or at least in development, and frequently after certain capabilities of the SoS exist in practice (Krygiel, 1999; Sage and Culpan, 2003; Kalawsky et al, 2012b). Thus the overarching SoSE approach should not be thought of as an *ab initio* methodology but rather one intended to accelerate and better coordinate the realisation of the SoS capability (OSD, 2008). However, lessons and insights from the initial synthesis efforts can be used to shape later iterations of the SoS to support a migration to a more systemic SoSE approach.

Note that SoS exist and will evolve without overt SoSE, funding, dedicated roles, or even acknowledgement. These SoS may still be shaped, usually based on the drive of an individual rather than via the systemic approach offered by SoSE. The success of this approach is critically dependent upon the energy and presence of the champion and will often falter on their departure. Also this approach increasingly struggles to deal with the complexity of modern warfighting capabilities and fails to leverage the opportunity to shape the SoS during the capability development and acquisition phases.

There are many current SoS/capabilities efforts (including the Land Battlefield Operating Systems such as, land manoeuvre, land ISR, logistics, engineering, …), which are in the main only weakly coupled to the current acquisition process. The SoS input for these capabilities tends to be at the start (concepts and high-level needs) and end (force generation and operations) of the capability process. Thus, any implementation of a SoSE approach needs to address how the current efforts to identify and define SoS/capability concepts can enhance the SE of the component projects to deliver a more effective SoS. Similarly, the SoSE approach needs to provide lessons learnt mechanisms (feedback paths) from the force generation process to assist in shaping capability requirements and acquisition.

Cook et al (2012), that is Deliverable 3 from the research task that funded this report, summarises the success factors for SoSE. Table 1, and the others of its ilk that appear below, were developed from those published in that report. From reading the success factors, it can be seen that a socially-aware approach is needed that has a spiral nature and that, during the early spirals, the degree of rigour needs to reflect the resources allocated to the task and the relative maturity of the constituent systems compared with the SoS.

Section 5 discusses the selection of approach for land force capability.

*Table 1. Success factors associated with the selection of an overarching SoS approach*

| **Key Success Factors in SoS Engineering**<br>***Overarching Principles and Approach*** |
|---|
| 1. **SoSE can only commence when a SoS has been Acknowledged.** Acknowledged SoS have a governance structure, defined roles and responsibilities and resources allocated to the task. (OSD, 2008; Turner et al, 2009). |

2. **SoSE is not the same as traditional project-based SE.** Attempts to apply project-centric top-down SE to SoSE will not produce good outcomes (Norman and Kuras, 2006; Ireland, 2011; Dahmann et al., 2011; Stevens, 2011 & Kalawsky et al, 2012).
3. **SoSE requires a multi-methodological approach with high adaptivity.** This is because SoSE is too complex to tackle with a single worldview and a single methodology (Kline, 1995; Cook and Allison, 1998).
4. **It is necessary to design a specific SoS practice to meet each circumstance** as each military SoS has its own challenges and (OSD, 2008; Gorod et al, 2008, USAF 2005).
5. **It is essential to focus on the design strategy and on trades** both when the formal SoS is first established and throughout the SoS evolution (OSD, 2008).
6. **Organizational as well as technical issues need to be addressed.** This applies to decisions and SE trades and decisions (OSD, 2008; Stevens, 2011).
7. **Continuous characterisation of the evolving SoS is needed.** This would cover the current and forecast utilisation environments, the status of constituent systems, and technology (Norman and Kuras 2006; OSD, 2008).
8. **A SoSE Process that balances top-down and bottom-up analysis and synthesis is essential** (OSD, 2006; Stevens, 2011).
9. **It is vital to achieve constituent system project office buy-in.** It is also necessary to maintain it through rewards that incentivise project offices to deliver SoS outcomes not just constituent system outcomes (Norman and Kuras, 2005; OSD, 2008). It is essential to encourage constituent projects to take on the attributes of a "good" constituent system project (Dahmann and Baldwin, 2011).
10. **Metrics should be in place to assess the "goodness" of key stakeholder inputs to SoSE**. This particularly applies to the CONOPS (Turner et al, 2009). The metrics should measure:
    - Comprehensiveness of Stakeholder identification and participation
    - Stakeholder understanding of the SoS problem, constraints, solution trade space and potential solution concepts.
    - Determination of the most reasonable increment spiral durations
    - Ability of CONOPS to be achieved through existing enterprise architecture structure.
11. **The SoSE framework should identify outcome spaces at multiple levels of scale and from multiple points of view.** For example strategy, warfighting concepts, capability portfolios, projects, operations and sustainment (OSD, 2008, Norman and Kuras, 2006; Ireland, 2011).
12. **SoSE should be incremental and evolutionary.** Employ "spiral fieldings", each of which ends in defined SoS capabilities (Rechtin 1991; OSD, 2008; Norman and Kuras, 2006; Turner, 2009; Ireland, 2011).
13. **It is important to have a long-term roadmap of SoS evolution.** This will facilitate the progression from short-term fixes to an integrated-by-design approach. Nontheless, it is not sensible to try and define a detailed SoS state very far into the future; aim for a few years hence (OSD, 2008).
14. **The first iteration needs to be investigatory and pragmatic.** It is unlikely that the SoSE Team will have sufficient information to manage the iteration using project management principles, indeed during this phase, it is crucial to be pragmatic about the selection of process activities to be performed and SoSE artefacts to be produced (Dahmann et al, 2011). It is essential that the artefacts are chosen to be informative and of practical utility to the constituent program offices and reflect the SoSE resources allocated.
15. **The initial integration of SoS is most effectively done using integration enabling technologies.** Integration developments, "glueware", should be used to graft elements together, ie a bottom-up approach has merit (Norman and Kuras, 2006; OSD 2008).
16. **Adopt a minimal set SoS integration principles**. These are used to steer projects towards achieving outcomes that will facilitate integration with the SoS, this approach is particularly useful is the early iterations (Norman and Kuras, 2006; Kalawsky et al, 2012).

17. **Move to an architecture-informed SoSE approach as SoSI capability matures.** Model-driven enterprise architectures have been found to be effective in SoS coordination activities (USN, 2006a & b; OSD, 2008).

## 3.3 Organisational Roles and Responsibilities

Regardless of the approach chosen, it is clear that to efficiently integrate something as complex as the land force capability SoS that will involve many projects, there needs to be a small number of staff dedicated to specific SoSE roles and that there also needs to be SoS-related roles within the constituent system SPOs. These dedicated roles and responsibilities are a vital element of SoSE capability, without which progress is unlikely to occur and Lane (2009) provides guidance on how best to size these efforts based on around a dozen quantitative metrics used to characterise military SoS. The success factors for the Organisational Roles and Responsibilities Element are shown in Table 2.

*Table 2. Success factors associated with organisational roles and responsibilities*

**Key Success Factors in SoS Engineering**
***Organisational Roles and Responsibilities***

18. **The systems engineers at the SoS level undertake different roles from those at the constituent system level** (OSD, 2008).
19. **Success depends on the ability of SoS managers to work across systems and balance technical and nontechnical issues.** This requires experienced, capable SoS managers and SE teams (OSD, 2008).
20. **The SoS Systems Engineering Team should explicitly articulate how the program will manage all requirements** (statutory, regulatory, derived, certification) (OSD, 2008).

## 3.4 Discussion on SoS Engineering Environments

Just as it is inconceivable to undertake systems engineering activities within a project without appropriate tools, the complexity of the SoSE challenge is such that it is vital to employ tools. These tools need to be selected to support the approach chosen but as a minimum these tools will need to support SoS definition, architectural design, engineering analysis, modelling and simulation, knowledge management, and testing and experimentation. It is vital that these tools can provide value without requiring all the detail of the component systems.

For convenience, we have included the SoS Test and Evaluation facilities and environments into this element. These would comprise a combination of SoS-specific aspects and general Defence engineering infrastructure.

The success factors for the SoS Engineering Environments Element are shown in Table 3.

*Table 3. Success factors associated with the SoS Engineering Environments*

**Key Success Factors in SoS Engineering**
***SoS Engineering Environments***

21. **Collaborative design and decision support environments are essential.** These are needed to facilitate communication between warfighters, SoS engineering, design teams of component systems, and other stakeholders (Norman and Kuras, 2006; Stevens, 2011 & Freeman, 2012).
22. **Validated Federations of simulations are needed to perform SoS performance assessment and utility analysis** (Rumford, 2008 & Stevens, 2011).
23. **"Discovery engineering" facilities that can support prototypes, experiments, and playgrounds are essential.** These are needed to demonstrate the utility of proposed constituent systems and de-risk SoS integration (Norman and Kuras, 2006 & Kalawsky et al. 2012).
24. **Effective SoSE and information management tools are essential** (OSD, 2008). These are needed to support and record SoS design and design rationale. Commonality of tools is, at present, the only effective way to achieve to support the generation of SoS artefacts and reuse.
25. **T&E facilities are needed to assess the evolving performance of the SoS at defined opportunities.**
26. Establish a SoS engineering culture within the capability development and acquisition community.

## 3.5 Discussion on SoSE Personnel

SoSE success relies on employing personnel possessing key SoSE competencies. Many of these competencies are in the leadership and social skills areas but high-level SE technical competencies are also needed. Recent seminal work provides a good insight into the competencies required to succeed in SoSE engineering and management roles. The UK MoD competency framework for "Systems People" (Oxenham and Swales, 2010) draws on psychological research in the UK to define the types of people needed for this type of work, whereas INCOSE (2010) provides a competency framework that can be profiled for the technical and managerial competencies that people need to exhibit to deliver good SoS outcomes. It is recognised that these people will be high achievers with broad, successful career backgrounds and they can be expected to have risen to executive managerial positions. Notwithstanding this, there are models from overseas that demonstrate that these people can be sourced and nurtured successfully.

The success factors for SoSE personnel are given in Table 4.

*Table 4. Success factors associated with the SoSE personnel*

**Key Success Factors in SoS Engineering**
***SoSE Personnel***

27. **It is necessary to identify and manage critical workforce competencies.** It is also essential to recognise that the competency and personal attribute profiles for SoS systems engineers are different from that needed for project systems engineers (Turner et al, 2009; Freeman, 2012).
28. **Innovative contracting arrangements are needed to secure the services of SoS SEs** (Cook 2012, Unewisse and Cook, 2011).

## 3.6 Discussion on SoS Training

It is axiomatic that an enduring capability will require a well thought-through training component. Given the environment in which SoSE will operate, and the specialised, complex nature of the activity, several training packages will be needed.

- Executive training for incoming SoS program office staff – this training will need to cover SoSE principles, roles and responsibilities, introduction to SoSE practices, and the use of the SoSE environment.
- Model-based Systems Engineering training for the SoSE processes and tools employed. This would be needed for several levels: supervised practitioner, practitioner, and expert.
- SoSE soft skills training to maximise the potential for synergistic collaboration between the stakeholder groups.

The success factors for SoSE training are given in Table 5.

*Table 5. Success factors associated with the SoS training*

**Key Success Factors in SoS Engineering**
***SoS Training***

29. **A structured formation path is needed to develop SoS personnel.** (Freeman, 2012; Cook 2012).
30. **SoS training will need to include training programs for all SoS stakeholder groups.** (Freeman, 2012).
31. **A SoS Engineering culture must be established in which automatic consideration of the SoS requirement, implications and impact are considered by all stakeholders of the capability acquisition and force generation processes (Blockley & Godfrey, 2000)..**

## 3.7 SoS System Design and Synthesis

Over the last twenty years, a specific set of SoSE design and synthesis approaches has been developed and assessed. The success factors for these are given in Table 6.

*Table 6. Success factors associated with the SoS design and synthesis*

**Key Success Factors in SoS Engineering**
***SoSE Design and Synthesis***

32. **SoS-level end-to-end performance, behavioural, and utility analyses are essential** (OSD, 2008).
33. **SoS solutions should be based on open systems techniques and loose coupling** (OSD, 2008; Norman and Kuras, 2006).
34. **There is a need for "glueware".** The more independent the constituent systems projects have been, the greater the likely level of glueware needed (Norman and Kuras, 2006).
35. **"Discovery engineering" (prototypes, experiments, playgrounds, etc.) is essential to recognise "goodness" in constituent systems** (Norman and Kuras, 2006).
36. **SoSE strategy needs to include early and iterative implementation on a development environment or part of the SoS** (OSD, 2008).
37. **The SoS SE Team will need to identify and disseminate the information architecture.** This will form the basis for collaboration and the technical standards that will apply to SoS (e.g. CIOG, 2012). The SoS SE Team will also need to develop a technical response to achieving and assessing conformance to the above (OSD, 2008).
38. **A key activity in SoSE is understanding the nature of constituent systems and technical interfaces between them** (OSD, 2008; Kalawsky et al 2012). Collecting, storing and maintaining this information is key to SoS analysis and update planning and implementation. To the greatest extent possible, this information needs to be maintained by the constituent system SPOs because the SoS PO will never have the resources to undertake such as large task.
39. **SoS success hinges on succeeding in Human Systems Integration.** These needs to be considered at both the constituent system level and the level of the SoS.
40. **SoSE needs to co-evolve with the relevant doctrine and standard operating procedures in order to realise the potential of the SoS.**
41. **Effective processes to capture lessons learned from force generation and operations are essential to ensure alignment between SoSE and SoS user needs.** This is often stated by rarely implemented in practice.

## 3.8 SoS Test and Evaluation

SoS T&E is now considered one of the major challenges for both the T&E community and the SE community (Dahmann and Heilmann, 2012). Building on the experience of the last 20 years, SoS T&E has now identified the success factors given in Table 7.

*Table 7. Success factors associated with the SoS test and evaluation*

| **Key Success Factors in SoS Engineering**<br>***SoSE Test and Evaluation*** |
|---|
| 42. **Define a best practices model for SoS T&E.** SoS T&E should be used as a continuous improvement process to provide supporting capabilities and limitations information for end users and feedback to SoS and System SE teams toward evolution of the SoS. (Wilson et al, 2011). |
| 43. **Define SoS capability test approach.** Rethink T&E of systems in an operational context and systems interoperability away from system testing toward integrated capability SoS testing. (Wilson et al, 2011). |
| 44. **Define characteristics of successful T&E.** Identify the process by which we can change and influence the governance of SoS. Mature and improve templates to define a minimum set of characteristics that are required to govern SoS T&E efforts. (Wilson et al, 2011). |
| 45. **Recognise and employ SoS guidance.** Ensure that guidance or SoS SE is recognized and employed on growing numbers of SoSs. (Wilson et al, 2011). |

## 3.9 Discussion on SoSE Research and Development

The Canadian PRICIE capability framework explicitly lists R&D as one of its core headline inputs to capability. This reflects their view that any defence capability requires R&D to maintain long-term effectiveness. Given that SoSE is still evolving internationally and that Australian Defence SoSE practice is yet to emerge, there are many research topics that require attention. The list below, consolidated from Valerdi et al (2008), provides a consensus of research topics produced during a meeting of US commercial, defence industry, and academic cognoscenti:

- Determine how to architect and evolve no-single-owner SoS through studying successful approaches and innovative practice. Specific issues include:
    - Overall approach selection
    - Evolution and guided emergence
    - Definition, tailoring, and application of SoSE artefacts
    - Maturation of model-based systems engineering approaches
- Determine how best to achieve SoS attributes (SoS 'ilities) such as security, adaptability, flexibility, agility, scalability, modularity, sustainability, resilience, net-centric vulnerability.
- Determine how best to identify and form SoS systems engineers and how to extend the human limits to handling complexity. Technical approaches to the latter would include enhanced knowledge management, data mining, automated reasoning under uncertainty about SE artefacts such as requirements specifications, SysML representations, etc.

More recently, Rhodes (2012) recognised that systems-of-systems research, because of the breadth of its contributing disciplines, required synthesis and cataloguing in a way that makes the literature and practice accessible to researchers, educators and the practitioner

community. Rhodes through the Systems Engineering Advancement Research Initiative (SEAri), is gathering international collaborators to advance this work and the first author of this report is to become involved and bring the fruits of this research back to Australia.

In addition, there is a need to effectively capture the SoSE lessons and insights to shape the next cycle of the SoS development.

The success factors for SoSE research and development are given in Table 7.

*Table 8. Success factors associated with the SoS research and development*

| Key Success Factors in SoS Engineering<br>***SoSE Research and Development*** |
|---|
| 46. **It is necessary to establish research programs that can tackle the SoSE challenge at multiple timescales.** It is necessary to develop approaches, methods, tools and techniques that can address today's SoSE capability issues as well as identifying practices for the medium and long term (Freeman, 2012).<br>47. **SoSE is a practice-based discipline and evidence will be needed from practice to validate proposed innovations in SoSE** (Boehm, 2012). |

# 4. Towards an outline of a Land SoSE methodology

## 4.1 Background

There are several schools of thought in SoSE. The first is that SoSE can be achieved through operating Traditional (project-based) Systems Engineering (TSE) at the next level up and adding some additional processes and artefacts. We shall call this the *TSE School*. Indeed the original work on architecture frameworks and the views followed this paradigm (Levis and Wagenhals, 2000) as did the US Naval Systems of Systems SE Guidebook (USN, 2006 a&b).

Perhaps the antithesis of this is the approach spearheaded by the New England Complex Systems Institute and Mitre that we will call the *Massachusetts School* that is based on complexity theory. This approach strongly advocates that the top-down classical TSE approach is not well suited to SoSE because it cannot handle the complexity of SoS and because the preconditions for TSE to be successful are not evident in SoS (Bar-Yam, 2003; Norman, 2005; Norman and Kuras, 2006; DeRosa et al, 2008). Norman (2005) lists these preconditions as:

- The specific desired outcome must be known a priori, and it must be clear and unambiguous (implied in this is that the edges of the system, and thus responsibility, are clear and known);
- There must be a single, common manager who is able to make decisions about allocating available resources to ensure completion;
- Change is introduced and managed centrally;
- There must be "fungible" resources (that is money, people, time, etc.) which can be applied and reallocated as needed.

In response to the inappropriateness of TSE for SoS problems, Norman and Kuras (2006) formulate Complex Systems Engineering that is described by a number of principles, many of which can be found in commercial practices and the management literature.

Yet another approach, which we shall call the *British Soft Systems School*, is strongly motivated by soft systems thinking as advocated by Checkland and Scholes (1999) and Hitchins (2003). This school focuses on achieving shared meaning and objectives across the stakeholder group and identifying different types of SoSE against various perspectives, namely, product, service, operational, enterprise and TSE subscribers, and across Hitchins' Five Layers Model of Systems Engineering (INCOSE UK, 2010). This school has the capacity to embrace the other schools but what it brings in breadth and philosophical underpinnings it lacks in specifics.

What we are seeking is to define an operational approach for land force capability development that draws on all available approaches while meeting the constraints and realities of the Australian defence situation. The current US DoD approach, derived from the TSE School, offers this as potentially does what we shall call the *European School* that is described by Kalawsky et al. (2012), which provides fresh ideas based on contract-based (or service-based) design, commercial methodologies, semantic modelling and simulation, and

upgraded SoSE tools. Given the maturity of the US DoD approach, we will use this as a basis from which to design a land force capability SoS approach.

## 4.2 The Australian Defence Enterprise Environment

The Australian Defence Enterprise environment is rather different from that of our allies and this impacts strongly on the type of SoSE that would work well in this country. These differences stem from the fact that Defence SoSE is not established in any formal way in Australia, and this being the case, the contemporary literature indicates that it would be premature to employ an architecture-driven methodology in the first instance. In addition, the Australian Defence Enterprise does not possess the SoS-level of SE capability that is found in many overseas countries (Unewisse and Cook 2011a & b) and importantly it lacks the research, innovation, and education capability that could readily support the introduction of large-scale, highly-structured SoSE efforts: these would need to be grown in conjunction with the SoSE capability.

It would be fair to rate the Australian Defence SoS Capability Level on the SEI CMMI – Acquisition (SEI, 2010) scale as Level 0 "Incomplete", which is defined as a process that either is not performed or is partially performed. The insight from this statement is not so much an indictment of the current situation, but a realisation that to propose an elaborate approach would be premature. Rather, it would be better to aim for a maturity level of Level 1 "Initial" that would employ flexible processes, which would need to depend on the competencies of a few highly capable people as opposed to proven practices.

Furthermore, recent work[1] also indicates that a substantial, disciplined engineering approach would not receive traction within Defence for resources, social, staffing, and cultural reasons relating to the lack of impact of previous architecture-framework-based initiatives. We also know that there is no appetite for increasing staff levels inside Defence and hence we need an approach which is roughly cost-neutral compared with the status quo. Thus a new synthesis of the available approaches is essential.

## 4.3 A Starting Point: The US DoD Approach

The Systems Engineering Guide for Systems of Systems (OSD, 2008), enumerates seven SoSE Elements (principal activities), five Focus Areas for SoSE management, 16 processes and five SoSE Principles that have found utility across a range of US SoS developments. These are shown in Table 7. This was essentially the starting point for the ongoing evolution of the US DoD approach to SoSE. We note this initial set of concepts relates to the US acquisition processes and the complementary T&E processes did not receive equal billing at that time. Considerable further work by the US DoD addressed this issue and focussed on operationalizing the concepts (Dahmann and Heilman, 2012; Dahmann 2012). The outcome of this work is embodied within the wave representation of the spiral development model (Dahmann et al., 2011), which is centred on orchestrating the evolution of a SoS towards defined milestones, see Figure 3.

[1] Interview analysis from the SOS PIC Scoping Study and the SoS PIC Health Check Study.

*Table 9. Key Concepts from the Systems Engineering Guide for Systems of Systems (OSD, 2008)*

**Key Concepts from the Systems Engineering Guide for Systems of Systems**

***Core SoSE Elements***

1. Translating SoS Capability Objectives into High-Level SoS Requirements.
2. Understanding the Constituent Systems and Their Relationships over Time.
3. Assessing Extent to Which SoS Performance Meets Capability Objectives over Time.
4. Developing, Evolving and Maintaining an Architecture for the SoS.
5. Monitoring and Assessing Potential Impacts of Changes on SoS Performance.
6. Addressing SoS Requirements and Solution Options.
7. Orchestrating Upgrades to SoS.

***SoSE Principles***

1. Addressing organizational as well as technical issues in making SE trades and decisions.
2. Acknowledging the different roles of systems engineers at the system versus the SoS level and the relationship between the SE done at the two levels.
3. Conducting balanced technical management of the SoS.
4. Using an architecture based on open systems and loose coupling.
5. Focusing on the design strategy and trades both when the formal SoS is first established and throughout the SoS evolution.

***Focus Areas for SoSE Management***

1. Program Requirements: The SoS SEP should define how the program will manage all requirements (statutory, regulatory, derived, certification).
2. Technical Staffing and Organization Planning: The SEP should show how the program will structure and organize the program team to satisfy requirements.
3. Technical Baseline Management: The SEP should establish a technical baseline approach.
4. Technical Review Planning: The SEP should show how the program will manage the technical effort, including the technical baselines, through event-based technical reviews.
5. Integration with Overall Management of the Program: The SEP should link SE to other management efforts, including the Acquisition Strategy, test planning, sustainment planning, configuration management, risk management, and life-cycle management.

***Relationship between SoSE Core Elements and SoSE Processes***

| | Technical Processes | | | | | | | | Technical Management Processes | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Rqts Devl | Logical Analysis | Design Solution | Implement | Integrate | Verify | Validate | Transition | Decision Analysis | Tech Planning | Tech Assess | Rqts Mgmt | Risk Mgmt | Config Mgmt | Data Mgmt | Interface Mgmt |
| Translating Capability Objectives | X | | | | | | | | | | | X | X | X | X | |
| Understanding Systems and Relationships | | X | | | | | | | | | | | X | X | X | X |
| Assessing Performance to Capability Objectives | | | | | | | X | | X | | X | | X | | X | |
| Developing and Evolving an SoS Architecture | X | X | X | | | | | | X | X | | X | X | X | X | X |
| Monitoring and Assessing Changes | | | | | | | | | X | | | | X | X | X | X |
| Addressing Requirements and Solution Options | X | | X | | | | | | X | X | | X | X | X | X | X |
| Orchestrating Upgrades to SoS | | | | X | X | X | X | X | X | | X | X | X | | X | X |

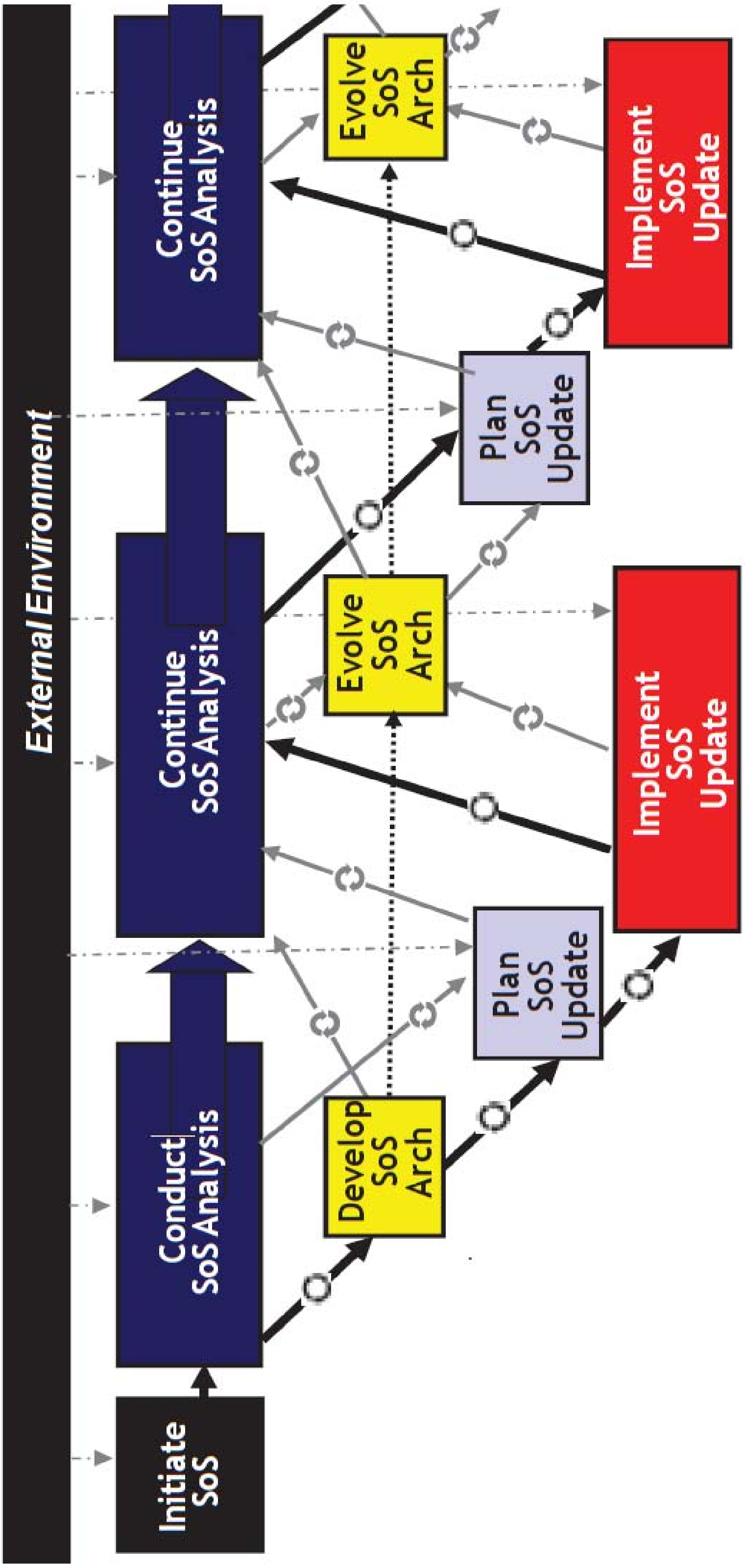



*Figure 3. The SoSE Wave Model (Dahmann et al., 2011)*

Dahmann and Heilmann (2012) provide guidance on the principal activities that a SoS program office would conduct and the key artefacts that US DoD would expect to see produced as listed in Table 8 extracted from Dahmann (2012). Those artefacts in bold within Table 8 are of particular significance to SoS Test and Evaluation activities. Even this carefully considered set of artefacts may prove challenging in the Australian context that would be characterised by relatively small SoSE teams. Hence the selection and definition of SoSE artefacts would be an important activity during the SoSE initialisation stage.

*Table 8. SoSE Artefacts produced in each of the Wave Model steps*

| Step in Model | Artifacts |
|---|---|
| **SoS Analysis:** Provides an analysis of the "as is" SoS and the basis for SoS evolution by establishing an initial SoS baseline and developing initial plans for the SoS engineering efforts. | Characterize SoS<br>• **Capability objectives**<br>• **SoS CONOPs**<br>• Constituent System Info<br>• SoS Technical Baselines<br>• **SoS Performance Measures &Methods**<br>• **SoS Performance Data**<br>• SoS Requirement Space<br>• SoS Risks & Mitigations Plan for SoS SE<br>• SE Planning Elements<br>• SoS Master Plan<br>• Agreements |
| **Develop and Evolve SoS Architecture:** Develops and evolves the persistent technical framework for addressing SoS evolution and a migration plan identifying risks and mitigations. | • SoS Architecture |
| **Plan SoS Update:** Evaluates the SoS priorities, options and backlogs to define the plan for the next SoS upgrade cycle. | • Allocated baseline<br>• Risks and mitigations<br>• **Agreements**<br>• Implementation, Integration & **Test Plans**<br>• Integrated Master Schedule (IMS)<br>• Updated Master Plan, Technical Baselines, and Requirements Space |
| **Implement SoS Update:** SoS SE team monitors systems implementation and test and leads SoS integration and test. | • **SoS Test Report**<br>  • **SoS Technical Plans, Requirements Space, Performance Data**<br>  • **System Test Reports**<br>• SoS IMS<br>• SoS Technical Baselines |

## 4.4 Adapting the US DoD approach to suit the Australian Context

### 4.4.1 Guiding Principles

Internationally, large architecture-framework-based approaches have not always been found to be effective for reasons such as the dynamism of the environment (the rate of change of constituent systems exceeds the capability of the architecture team to record it and use it to inform action); the lack of ability for central planning and design to influence constituent systems in a timely manner; and the sheer scale of the effort required to capture and maintain a Defence Architecture Framework model using a rigorous approach (Kalawsky et al, 2012). The bottom-up, equipment-driven SoSE approaches, see for example Norman and Kuras (2005), have found utility when there are many systems to integrate and little opportunity to shape the development of constituent systems. Thus, given the environmental factors and the fact that SoSE is yet to be formalised within Defence, the US DoD approach will need to be tailored carefully.

We suggest that it would be best to start from the position that the task of land force capability SoSE activity in the short term is to maximise the integration of current and planned land capabilities with as little impact on the constituent systems as possible.

Morris et al (2006) provides a useful conceptual framework for an appropriate approach:

> "Collaborative system-of-systems governance involves abandoning the notion of rigid top-down governance of … processes, standards, and procedures and adopting peer-to-peer approaches. Such collaborative system-of-systems governance is clearly at odds with the natural tendency of business and military organizations, because it means that the "chain of command" must evolve to a "web of shared interest." Collaborative system-of-systems governance requires cooperation between separate authorities, even when there is no formal agreement."

Figure 4 illustrates the key players in an Australian Defence SoSE context. Imperial projects are those that, by their very scale and influence, shape many other projects and existing capabilities. Examples include Land 400 Land Combat Vehicle System, Air 6000 Air Combat Capability, AIR 5077 Airborne Early Warning and Control System, SEA 4000 Air Warfare Destroyer, AIR 7000 Maritime Patrol Aircraft Replacement. Component projects provide specific capabilities such as sensing systems, weapons systems and training systems. In contrast, "glue" projects are enabling projects that provide the enabling infrastructure for C4ISREW such as communication links, command support systems and network management. It is envisaged that the SoS Team would comprise a few individuals that would be tasked with the roles and responsibilities described below. The arrows on Figure 4 show lines of influence and agreement, with the size of the arrow indicating the relative complexity of the link. These entities work within an SoSE engineering environment that is informed by the constraints listed earlier, and by the efforts of organisational elements within Defence tasked with achieving network integration (e.g. the Land Network Integration Centre, (Rawlinson, 2011), the Chief Information Officer Group, The Tactical Information Exchange Integration Office, Defence Systems Integration Technical Advisory, etc.).

It is important to appreciate that the projects each have their own asynchronous lifecycles with the "glue" projects potentially being the shortest, extending up to the imperial projects such as military vehicles that span decades.

In practise, the overall SoSE Team is likely to be a distributed construct and could comprise members from one or more of the SoSE entities enumerated in Figure 4. The first ("1" in Figure 4) would be an operational capability-based, acknowledged SoSE Team, for example, joint amphibious capability or joint fires. Although these dedicated SoSE Teams may have considerable authority and influence, particularly should they be in direct support to a cross-project Program Management Steering Group (PMSG) oversighting issues across multiple projects, they will tend to be small and are unlikely to directly control funds. Note that current PMSGs are not, in general, supported by a SoSE Team.

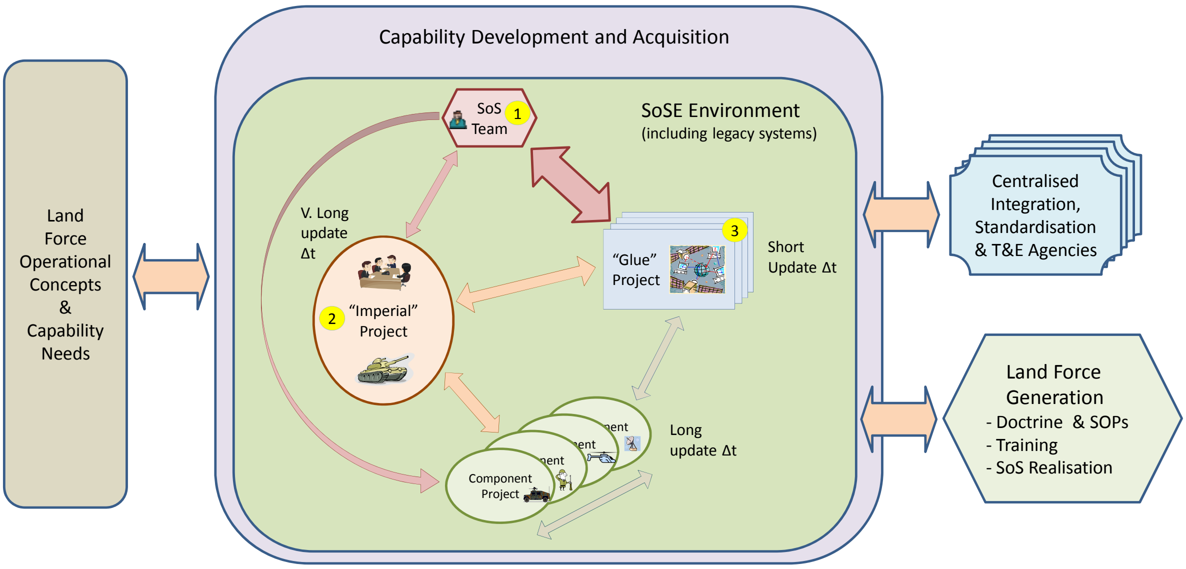



*Figure 4. Key players in Australian Defence SoSE*

SoSE Teams can also be located within an "imperial project" ("2" in Figure 4). These teams have the advantage of direct authority within the large-scale project and, through the dominant role of the imperial project, plus access to comparatively high levels of funding, are able to shape the associated projects into a SoS. A major limitation of these SoSE Teams is the constraint placed on them to limit their scope to the immediate focus on the project.

Finally, SoSE Teams will also be found within the major 'glue' projects. This is an almost inevitable consequence of the nature of these projects, as they provide the interfaces between the other projects and also have the most holistic approach to the overall SoS. As a consequence, there is a tendency for the other projects to transfer much of their SoS integration responsibilities and risks to the 'glue' projects. Unfortunately, the 'glue' projects

are rarely funded to address the scope of the broader integration challenges transferred to them by the rest of the constituent SoS projects.

A relatively recent development is the emergence of very senior PMSGs up to the 3-star level that have the authority to direct individual projects and redirect funds. However, this high-level governance function tends to be unsupported by the sort of significant SoSE support that could be provided by a dedicated SoSE Team. A possible approach would be to establish a small dedicated SoSE team to support the senior PMSG, and then coordinate the efforts of the distributed (and hopefully augmented) SoSE Teams within the "glue" and/or "imperial" projects.

### 4.4.2 Review of success factors

Below is a summary of the SoSE success factors that are salient to the design of a nascent SoSE approach to suit the land force capability challenge.

- SoS function needs to be formally acknowledged, resourced and established.
- The first activity will be to identify the capability needs in the form of an agreed capability objectives and concept of operations.
- The approach will have to be designed to suit the need (in full appreciation that it will initially be investigatory and pragmatic) where:
    - The activities will be continuous and iterative.
    - The initial iteration will be largely bottom-up and driven by the in-service or contracted project systems.
    - Resource will be modest - the SoS Team will be small.
    - A minimal set of relatively simple artefacts are used for the initial iteration.
    - SoS Team activities are informed by a minimal set of rules of the games rather than process.
- Constituent system SPOs will need to be tasked to provide (and keep configuration managed) salient project information to the SoS Team.
- The key SoSE artefact for the Land SoSE activities will be the Agreements between the SoS Team and the constituent system SPOs.
- The approach needs to be socially aware, have SoS Teams work across systems and balance technical and non-technical issues.
- The approach will need to be compatible with the SoSE environment available.

Furthermore, TTCP (2011) strongly advocates that one of the principal lessons learned over recent years in defence SoS practice is that it is imperative that the SoSE effort is aligned with resources. Resources are allocated to projects and as such the constituent project SPOs need to take on as many tasks as possible, such as the provision of SoS-relevant configuration-managed project information, the establishment and execution of SoSE agreements, and SoS compatibility de-risking. The SoS Team is unlikely ever to have the resources to collect and maintain the project information or conduct extensive analysis or testing.

Given the current land force integration state (Rawlinson, 2011), it is a reasonable assertion that the initial land force capability SoS iteration would be based on the application of SoS

enabling technologies ("glueware") to achieve interoperability between in-service capabilities and those soon to enter service. The provision of the materiel to achieve the integration will be provided by what we have termed "glue" projects in Figure 4. Thus the design of the SoSE approach needs to address how the SoS integration principles and success factors would be implemented if a glue project were the main driving force for SoS integration.

In summary, the success factors coupled with the environmental realities discussed earlier indicate the need to adopt a lightweight approach that would establish a small SoSE Team comprising highly competent people that could operate effectively with minimal formal structure, informal co-ordination meetings, lightweight processes, and minimal infrastructure.

### 4.4.3 SoS Activities during Early Iterations

#### *4.4.3.1 SoS Team Initialisation*

SoSE activities commence when a SoS has been acknowledged, resources are allocated, and the SoSE Team is appointed. The first task of the SoS Team would be to establish the boundary of the SoS, its context, the stakeholder group and the capability needs it is being assembled to fulfil. This work would result in the ***Capability Objectives*** artefact that would describe the capabilities needed by the user, ideally based on some definitive or authoritative materials, but interpreted through workshops and war games. In contrast to conventional project systems engineering, the SoSE Team would have the ongoing role of translating capability needs into technical requirements and identifying new needs as the situation changes and the SoS evolves. (After initialisation, the latter activity is bundled with SoS Analysis, see below.)

The SoSE Team would work with the key military stakeholders to establish how constituent systems in the SoS will be employed in an operational setting and with SPOs to define the functionality expected from each constituent system. Mission thread analysis workshops or similar (Wood et al, 2011) have proven effective in producing this information. The results from this activity would be recorded in a ***SoS Concepts of Operations*** (SoS CONOPS).

At this stage, initial ***Constituent System Information*** comprising technical and programmatic information is provided to the SoSE Team by the SPOs providing the constituent systems. SoS-level ***Risks and Mitigations*** are also identified and the tracking and updating processes initiated.

SoS T&E Planning commences at this stage and is refined during the SoS Analysis activity. Dahmann and Heilmann (2012), OSD (2008), among others, note that comprehensive OT&E of a substantial system is impractical and hence significant thought needs to be given to addressing the SoS T&E issues that are enumerated in Section 6.2 and in the consequent planning of a meaningful T&E program.

During the initialisation phase, the first version of the ***Agreements*** between the SoS participants (the four groups shown in Figure 4) should be drafted. The ***Agreements*** formalize roles and responsibilities of SoS participants at a broad level and record organizational relationships, roles, and responsibilities, and specific commitments of participants in a

development increment. It is recognised that because SoS cut across organizational boundaries, agreements are critical to SoSE success (Dahmann, 2012). It is critical that the relevant SoS Plan and T&E elements be accepted by the constituent projects and the other relevant agencies (e.g. doctrine developers) as most of the implementation will need to be undertaken by these SoS participants.

#### *4.4.3.2 SoS Analysis*

During SoS Analysis, the SoS systems engineer would be responsible for working with the SoS manager and other stakeholders to take the Capability Objectives, SoS CONOPS and System Information and translate the capability needs statements into key ***SoS-level Requirements*** that can inform the production of a ***SoS Technical Baseline, SoS Performance Data***, and ***SoS Performance Measures and Methods.*** As the understanding of the SoS matures, the technical baseline would expand to contain analogues of many conventional SE artefacts such as a functional decomposition to constituent systems, functional flow definition in the form of a mission thread analysis, performance allocation, etc. In order to produce the artefacts listed it would be necessary to perform a performance allocation between constituent systems. It must be appreciated that, in the first instance, this could not be done with any precision but the aim would be to improve this and other aspects of the SoS Analysis with each iteration. The information produced during the analysis provides the foundation for the technical planning needed to evolve the capability over time and artefacts such as the ***SoS Planning Elements***, the ***SoS Master Plan***. These need not be detailed and could take the form of a roadmap. Updated ***Agreements*** between the stakeholder communities could also be used to document mutual responsibilities between the stakeholders.

The SoS analysis also needs to assess the level of SoS integration readiness of the constituent systems and then identify the level of system integration required from each constituent system. This will establish some of the SoS integration risks as well as identifying both requirements and risks that need to be addressed by the constituent SPOs. Such analysis is complicated by the asynchronous development and delivery of the constituent project as well as new projects and systems being introduced. This requires the SoS planning to be able to evolve over time, shaping and incorporating additional systems and projects relevant to the ongoing development of the SoS.

#### *4.4.3.3 SoS Architecture Development*

The ***SoS Architecture*** defines the way the constituent systems work together and would include the functional analysis artefacts mentioned earlier that would describe the end-to-end functionality, data flow definition, functional interfaces, and communications. The SoS Architecture would need to map the SoS functional needs onto current and forthcoming constituent systems in order to support performance allocation and gap analysis.

It is important for SoS engineers to appreciate that the purpose of this activity is to obtain answers to specific short-term questions such as “What are the functional gaps?” or “What capabilities might need to be enhanced?”, not to produce a comprehensive architecture framework description *per se*. Thus the approaches used to record and reason about the architecture need to be matched to the questions to be answered and the resources available. As a consequence, specific architecture products should be carefully and sparingly selected to

deliver the required answers and insights. Nevertheless, there are likely to be a large number of SoS artefacts and architecture products. Where possible, the SoSE Team should seek to engage the relevant constituent SPOs to generate many of the artefacts. The small SoS Team should focus on the major whole-of-capability artefacts and shaping and synthesising the outputs of the constituent projects.

#### *4.4.3.4 SoS Update Planning*

Armed with the fruits of the analysis and architecture development activities, the next activity is to identify those needs and gaps to be addressed in the next iteration cycle. A systems engineering design cycle then follows to identify the preferred solution for addressing the selected capability gaps. This leads to updated baselines and other artefacts mentioned earlier, ***Implementation, Integration and Test Plans***, and an ***Integrated Master Schedule***. New projects are then established to produce or modify constituent systems to implement in accordance with these plans. These plans and schedules need to be agreed by the constituent SPOs and, as relevant, incorporated into their own internal plans and schedules.

Note that longer-term issues and gaps can be captured in a lower resolution SoS roadmap.

#### *4.4.3.5 SoS Update Implementation*

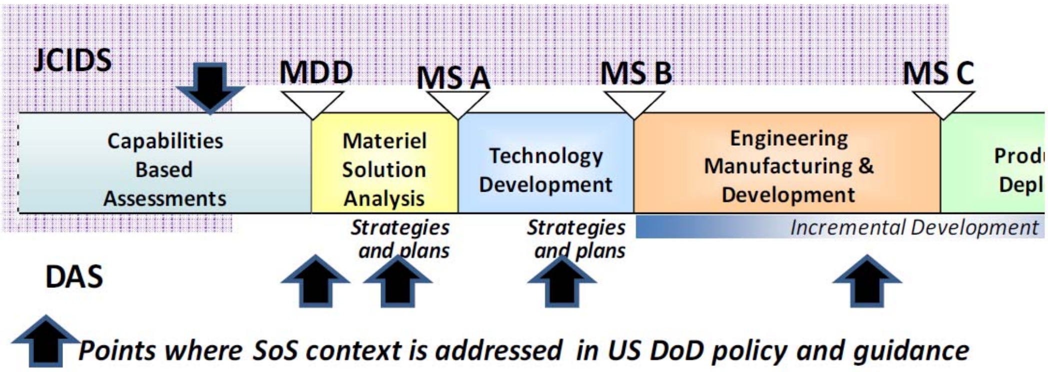
This activity monitors the implementations that are being managed by the SPOs at the constituent system level and compares them against the SoS Integrated Master Schedule, the Risk and Mitigation Plan and the known SoS dependencies. In parallel, the SoS team plans and then conducts SoS-level testing and evaluation in accordance with the plans and produces a ***SoS Test and Evaluation Report***. The activity continues on to update the as-is technical baseline and other artefacts to reflect the evolving state of the SoS.

## 4.5 Addressing SoS Challenges from a Constituent System SPOs Perspective

Dahmann and Baldwin (2011) state that little attention has been paid to how systems engineers within SPOs should address the engineering of new constituent systems to enable them to support current and future SoS. Notwithstanding this, they have found through a search of contemporary US capability development and acquisition instructions that there are several points where DoD policy or guidance calls for the SoS context to be addressed. These are illustrated against the development lifecycle in Figure 5.

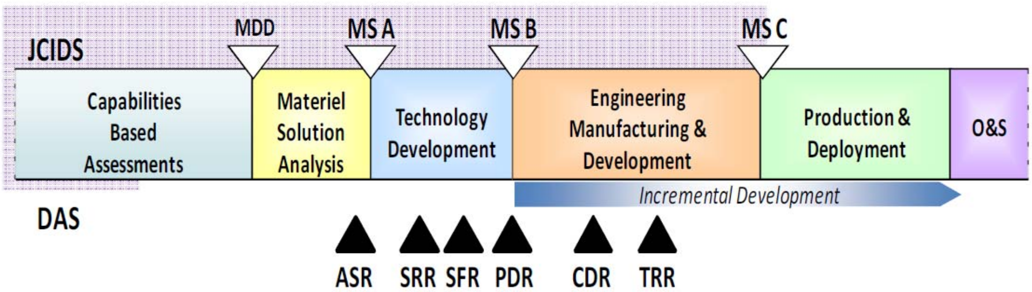
Dahmann and Baldwin (2011) go on to state that new US policy on development planning has instituted a policy shift from a platform focus to a capability focus, and this change requires consideration of the context, particularly project interdependencies, at the Materiel Development Decision for a new acquisition program. They go on to say that current US acquisition policy also emphasizes the SoS context in key programmatic and technical plans including the acquisition strategy, systems engineering plan, and test and evaluation plan and that these are reviewed at major milestones. Furthermore, they state that US SE guidance emphasizes the SoS context as part of program formulation, requirements, and integration

and that key SE technical reviews include considerations of interdependencies, interfaces, and information exchange requirements at the events shown in Figure 6.




| | |
|---|---|
| JCIDS | Joint Capabilities Integration Development System |
| DAS | Defense Acquisition System |
| MDD | Materiel Definition Document |
| MS A | Milestone A |
| MS B | Milestone B |
| MS C | Milestone C |

*Figure 5. Points where the SoS context of a constituent system is addressed (Dahmann and Baldwin, 2011)*




| | |
|---|---|
| ASR | Alternative System Review |
| SRR | Systems Requirements Review |
| SFR | System Functional Review |
| PDR | Preliminary Design Review |
| CDR | Critical Design Review |
| TRR | Test Readiness Review |

*Figure 6. US DoD Technical reviews that address the SoS context*

As with many aspects of policy, Dahmann and Baldwin (2011) recognise that there remain unanswered questions about how best to ensure that the intent of the policy and guidance can be thoughtfully enacted in practice.

The approach for integrating largely pre-existing systems advocated by the Massachusetts School, in particular Norman and Kuras (2006), address this issue by advocating the use of reward mechanisms to incentivise SPOs to develop their products and services in such a way as to maximise SoS outcomes. This has been found to be successful, but it will necessitate a

refocus of project priorities and the definition of projects' outcomes both at the constituent system level and at the SoS level. This would become a significant driver for shaping the agreements established between the SoSE Team and the SPOs.

Similarly, Dahmann and Baldwin (2011) discuss "good" behaviours to be encouraged within constituent system SPOS. These include:

- Understanding the role in the larger SoS capability, and considering this role when capturing requirements and designing the constituent system T&E plan;
- Devising designs that facilitate functionality changes and extensions and that possess adaptable interfaces;
- Employing short development cycles to provide more opportunities for aligning constituent system properties with SoS needs;
- Recognising that the SoS Team is a user of the project configuration management and requirements processes and tools and designing them to welcome outside inputs; and
- Employing a business model, which provides a way to support changes and address issues of maintenance.

In the short term, this is likely to require active participation by SoSE Team members in constituent project IPTs. Given the small size of the SoSE Team, this will constrain both the scale and number of SoSE efforts that can be initially pursued.

Over time, a combination of efforts including systems engineering training that incorporates SoS issues, implementation of high-level reporting and reward mechanisms for SoS risks and issues within projects, and cultural changes within the capability development, will increase the level of awareness and willingness to address SoS engineering and integration issues within the SPOs. As SoSE becomes a more accepted and ingrained element of the SPOs, the level of effort needed by the SoSE team in each project will decrease, allowing for increases in the scope and scale of the SoSs addressed – without large increases in personnel.

## 4.6 Requirements for a Land SoS support environment

First and foremost, the environment needed to support Land SoS development and evolution must achieve information integration. It must be able to import, catalogue and mine data and knowledge in whatever forms it is represented. At present, this represents a serious challenge because of the disparate information systems employed across Defence and the relative immaturity of the tools available to perform this function at the SoS level. The advent of the rollout of the DSTO Whole System Analytical Framework heralds an opportunity to capture project definition, planning scenarios, requirements and test concepts in coherent machine-readable form, and this represents a key enabler for a successful SoSE environment (Robinson, 2010), one that can transcend the contractual boundary (Do et al., 2011). Furthermore, the latest research in MBSE environments demonstrates promise in the integration of tool suites through bi-directional semantic translators between tool-specific representations and provides a comprehensive, operationalized MBSE environment that spans behaviour and relational modelling through to simulation of the final design implementation (Kalawsky et al., 2012b).

In the interim, conventional SE tools and knowledge management technology can be employed to good effect but it must be understood that the capability of the tools employed will drive the nature of the information collected and the level of abstraction selected. Note that implementing such MBSE tools will require increased investment in system engineering training as well as training in the MBSE tools themselves in order to realise their potential to support SoS integration.

## 4.7 Wider factors that shape the proposed Land SoS approach

As discussed in the section on the components of SoS capability, SoSE is a socio-technical challenge, and there are many social and cultural issues to address to transition from the entrenched, stovepiped approach to one that embraces that project outcomes and performance metrics, particularly those for communications and information system "glue" projects, need to reflect predominantly SoS metrics. It is something of an axiom in the SoSE research community (IEEE 2012) that SoSE is an intensely social activity, which presents many cultural, behavioural, ethical and organisational challenges to the inherently single-project acquisition ethos predominant in both the defence and civil sectors. For example, see Henshaw (2012). This is will need an active program to evolve the organisational culture towards a SoSE approach. This will involve a phased approach over a number of years to both grow the SoSE capabilities and to establish the acceptance of SoSE within Defence as an effective way to realise future integrated warfighting capabilities.

# 5. Towards Requirements and Specification Practices for Land Force Capability Integration

## 5.1 The Type of the Requirements Information Needed for SoSE

Firstly, from the foregoing, it is our belief that requirements and specification practices for land force capability integration will be strongly shaped by the overall SoSE approach adopted. In the tailored US DoD approach described above, requirements appear both at the SoS level and also exist for each constituent system.

At the land force capability level, Dahmann et al., (2010) state that SoS requirements explicitly do not take the form of requirements for a Major Capital Equipment (MCE) project; that is a large set (often thousands) of detailed operational requirements or specified technical requirements.

Rather SoS requirements are captured by three artefacts: the SoS Capability Objectives, the SoS Concept of Operations (CONOPS), and the SoS Requirements Space. A description of these artefacts largely due to Dahmann et al. (2010) appears below.

SoS Capability Objectives are a statement of top-level objectives for the SoS. They describe the capabilities needed by the user, ideally based on some definitive or authoritative materials (e.g., White Paper, Defence Capability Planning Guidance, strategies or Australian Capability Context Scenarios). They are used by the SoS Team and stakeholders as the foundation for SoS requirements, metrics, etc. The capability objectives provide a basis for translating operational needs into high-level requirements, assessing performance to capability objectives, and developing an architecture and solution options.

The SoS CONOPS describes how the functionality of the constituent systems in the SoS will be employed in an operational setting. The CONOPS is developed by the prospective operational users and with active participation from the SoS Team to describe the way users plan to operate and use constituent systems to achieve the objectives, as influenced by the various environments and conditions anticipated. The CONOPS is developed in parallel with the capability objectives and, as the capability objectives evolve, the CONOPS should evolve in detail, as well. The SoS Team and the SPOs use the CONOPS to define the SoS requirements space, to identify aspects of constituent systems, which could impact the SoS design, and to select performance metrics and test environments.

The SoS Requirements Space bounds the first-order SoS user needs (including operational tasks and missions) and defines the functions required to provide the capability across the range of user environments likely to be encountered. It should be noted that this artefact is a ‘requirements space’ versus a set of ‘requirements’, because in a SoS, ‘requirements’ are taken on by the constituent systems to meet the SoS. The requirements space includes both the SoS Capability Backlog and Problem Reports. It is developed by the SoSE Team in liaison with constituent system SE teams and with strong engagement with SoS and constituent system

operational communities. It is used by the SoSE Team and constituent system SE teams to: determine information needed to understand systems and relationships, compare performance to capability objectives, develop an SoS architecture, identify areas to be addressed in an increment(s), identify solution options, develop a plan for SoS increment(s), and develop a plan to test and evaluate the changes.

It can be seen that the three artefacts record information at a different level of abstraction from the Function and Performance Specification that is the principal requirements document used with the Australian Defence Capability Development process. Defence (2009), states that the FPS specifies the formal requirements for the Materiel System and provides the basis for design and qualification testing of the system. The FPS provides the vehicle for the capture of formal, verifiable and unambiguous requirements, effectively 'distilled' from the OCD. The FPS is intentionally written using formal language, with all requirements in the FPS traceable to needs identified in the OCD. The FPS becomes part of the contract between the Defence Materiel Organisation and the supplier. In contrast, the SoS Requirements Space is an interpretation of the SoS Capability Objectives and the SoS CONOPS by the SoS Team that is used for the purposes mentioned above and to shape the Agreements between the SoS Team and the constituent system SPOs. These agreements must facilitate both shaping the component projects (SPOs) to take into account the SoS requirements and shaping the SoS artefacts to take into account key drivers and constraints from the constituent projects.

We see that the most effective way of coordinating and managing the relationships necessary for a good SoSE outcome is through the Agreements. The definition of Agreements provided in Dahmann et al. (2010) states: The Agreements formalize roles and responsibilities of SoS participants at a broad level (e.g. Charter) as well as specific commitments of participants in a development increment. Because SoS cut across organizational boundaries, agreements are critical to SoS SE success. SoS and system management and SE teams (and contracting officers and commercial contractor representatives, as needed) define agreements among participants regarding organizational relationships, roles, and responsibilities, and to manage interactions of participants and other stakeholders. The SoSE Team should also facilitate appropriate agreements between the SoS constituent projects.

Recent research points to a richer use of agreements to achieve engineering outcomes in a SoS context. Kalawsky et al (2012a) proposes that commercial ideas can be brought to bear to tackle the vexing problem of integrating constituent systems into SoS through what is termed contract-based design where the contract encapsulates the conditions for correct integration as opposed to constituent system requirements and constraints. Quinton et al. (2010) state that contract and interface frameworks are emerging as the formalism of choice for system designs that require large and dispersed teams, or where the supply chain is complex. They go on to say that contracts are usually expressed as pairs of assumptions, or properties that the environment must satisfy, and guarantees, the properties that must be satisfied by each particular component. Ben-Hafaiedh et al. (2010) increases the sophistication of the contracting relationship by adding interfaces to make a 3-tuple.

Contract-based design is centred on forming SoS by integrating pre-existing, well-defined components. Initially these were software components but the technique is migrating to hardware also. Contract-based design uses formal mathematical foundations for contract

clauses and as such can support proofs and other forms of reasoning as well as automatic design. For example, if the assumptions of each component are contained in guarantees offered by constituent systems, then the SoS composition is termed "well formed" and will meet its specification. Contract-based design is seen as a major component of the European Commission research project '**D**esigning for **A**daptability and evolutio**N** in **S**ystem-of-systems **E**ngineering (DANSE) and Kalawsky et al. (2012) show how the contracts can be coupled to design and modelling and simulation tools to create and verify SoS compositions.

Similarly, Holt et al (2012) take a rich view of requirements that suits the needs of SoSE well in that they consider requirements to comprise business requirements, functional requirements and non-functional requirements (often termed constraints). The latter two categories are normally included in a project function and performance specification, whereas the business requirements are absent in that document, although aspects are included in other project documentation such as the Operational Concept Description and the Acquisition Business Case. Holt et al. show how the Systems Modelling Language (SysML) can be used to capture comprehensive requirements in hierarchical requirements diagrams, activity diagrams, sequence diagrams, state machine diagrams, block definition diagrams, and use cases. This is a rich way to record contracts and SysML has been shown to be able to be used for automatic design, functional modelling and simulation, detailed implementation and prototyping (Kalawsky et al., 2012a).

While the contract-based approach is yet to mature, the idea of setting up an agreement to supply (largely pre-existing) constituent systems based on high-level definitions of services and behaviours has much to commend it over the approach that expects thousands of detailed performance parameters to be known and quantitative performance thresholds defined before work commences. Indeed, this is how one buys complex items such as computers, smart phones, and cars in the civil sector. Such agreements, if coupled with appropriate reward and penalty mechanisms, would facilitate parallel action between the SoS constituent SPOs, and with the SoSE Team. However, care needs to be taken that the agreements incorporate sufficient flexibility to ensure that the parties to these agreements are able to evolve along with the evolving nature of an enduring SoS.

If such agreements are put in place to support SoS engineering and integration, then the maturity of the web of agreements between the SoS constituent SPOs and with the SoSE Team becomes a key metric for effective SoS integration processes.

## 5.2 An Evolving Requirements Practice for Land Forces Capability

Management of enduring SoS such as the land force capability would expect to cycle through many iterations of the Wave Model. In the early iterations, many of the constituent systems would either be in service or already specified and contracted against a detailed specification. In cases such as these, the work of the SoSE team is to understand how the SoS will be used and to identify gaps, interfacing difficulties and performance shortfalls, and to work with the constituent system SPO to effect small changes to meet the objectives of the SoS Milestones.

As the SoSE capability matures, greater value arises from increasing the degree of top-down SoS design until a middle-out approach is reached, which fully combines top-down strategic

drivers with bottom-up equipment and project realities that is driven by functions, often best expressed as mission threads. In common with strategic planning and systems engineering, in general, it is useful to start with the end in mind when undertaking SoSE. Thus, it is proposed that, even in early SoS iterations, SoS artefacts are produced, however embryonic. Foremost of these will be the three SoS artefacts that define the intent of the SoS: the SoS Capability Objectives, the SoS CONOPS, and the SoS Requirements Space. Initially these could take the form of short documents or posters even but, over time, they should migrate to something akin to the Whole-Systems Analytical Framework (WSAF) (Robinson et al., 2010). While WSAF was originally conceived for large projects, the projects to which it has been applied are SoS-type glue projects, for example Land 19 Phase 7, Ground Based Air Missile Defence, and Land 400, the Land Combat Vehicle System (LCVS), the Army's largest, most expensive and most complex major capability equipment project to date, that aims to deliver the mounted, close-combat capability to the land force from 2025. In Robinson's words:

> "As we know, the LAND 400 "model" is more than a series of traceable information. It includes additional information that provides a greater level of context and justification for the systems requirements and operational needs that is verging on "design rationale". Beyond "just" an enhanced traceability matrix and what should be an improved OCD and FPS (over the document-centric alternatives), what return on investment does this bring? In my view, this MBSE approach brings a return in investment through:
>
> - Extending SE practices to the enterprise level
> - Improved completeness of capability definition
> - Greater stakeholder engagement through effective visualisation
> - Traceability of designs
> - Capture of [SoS] design rationale
> - Good knowledge management through focussing on knowledge not documents
> - Simple knowledge dissemination - accessible by stakeholder groups
> - Improved risk identification and management."

If high-level ownership of the SoS Capability Objectives, the SoS CONOPS, and the SoS Requirements Space artefacts can be achieved, then these artefacts can support the governance and decision-making of the SoS. In particular, it will allow comparison of dissimilar system and project proposals based on their impacts to the SoS, resulting in more informed decision-making to deliver the broader SoS capability rather than consideration of project proposals in isolation.

Once SoSE tools reach maturity and are populated, then top-down design becomes possible and the SoS conceptual model can inform constituent system requirements. (Flanigan and Brouse (2012) propose a SoSE requirements allocation process based on traditional systems engineering that could be considered.) Until that time, the best avenue to influence projects and formalise the expectation of SoS needs and the contributions that fielded constituent systems would be expected to make to SoS, would be the Agreements between the SoSE Team

and the SPOs and, where appropriate, Agreements between the other parties shown in Figure 4.

We are proposing that the scope of the SoS Agreements proposed by Dahmann et al. (2010) be expanded to include:

- Role and responsibilities of both parties;
- Specific commitment of both parties to a SoS development increment including coordination meetings, demonstrations or other de-risking activities, constituent system project events, etc;
- Information to be provided from the SoSE Team, dissemination mechanisms and timeliness expectations (assumptions in contract-based design language);
- Mission functions and behaviours to be delivered by the constituent system (properties in contract-based design language);
- Interface definition at a high-level (interface definition in contract-based design language);
- How the functions and interfaces will be verified, e.g. demonstration on a SoS integration test bed;
- Information to be provided by the constituent system team and timeliness expectations; and
- Overarching drivers for and frameworks of agreements for the SoS to be endorsed by senior leadership / governance processes.

## 5.3 Multi-Scalar SoSE

Land force capability comprises multiple battlefield operating systems (BOS), which are SoS, or sub-SoS of the broader land force. This creates the opportunity for intermediate SoSE teams that build on the existing BOS capabilities such as fires, logistics, engineering, and ISR, and the established organisational and cultural frameworks that currently seek to address SoS in the land force. Such BOS-based SoSE teams should be able to be quickly established as they are both focused at a manageable level of complexity and build on established stakeholder communities across the relevant projects and land force organisations. The focused nature of the teams should also assist in relatively rapidly addressing the SoSE challenges of each BOS.

SoSE is still required at the land force level to facilitate the integration of the intermediate BOS SoS into larger force-level constructs. SoSE teams at this level would seek to shape the synthesis of the BOSs into combined-arms teams and undertake trade-offs between the potentially locally optimised BOS solutions to deliver more effective land force capability.

Such a multi-scalar approach to land SoSE should both enable a more rapid adoption of the SoSE approach in land and reduce the risks of trying to solve all of the SoS integration challenge in one monolithic SoSE effort. This would enable a phased implementation of SoSE allowing for growth of land SoSE team capacity and for an incremental learning approach to SoSE in land with later SoS teams learning from the experience of earlier efforts. Finally, such a multi-scalar approach would align with the distributed nature of the land SoS integration effort between multiple projects and the land force generation process.

Note that, although C4I can be regarded as another BOS capability, the reality is that these "glue" systems are ubiquitous within and between all the BOS SoS. As such, they are often best considered as a core enabler of the overall land force SoS. This will tend to result in a close relationship between these "glue" capabilities as a sub-SoS and the force-level SoSE team.

# 6. T&E processes for Land Force Capability integration

## 6.1 Challenges for SoS T&E

SoS T&E is not only perplexing because of the complexity of the SoS under consideration, but also because of how SoS are composed: they are formed from constituent systems, almost all of which are in different stages of their system lifecycle. Wilson et al, (2010) lists the SoS T&E challenges identified by the NDIA in 2009; the ones that relate to the Australian land force capability SoS are as follows:

- Requirements: If 'requirements' are not clearly specified up front for a SoS, what is the basis for T&E of an SoS?
- Metrics: What is the relationship between SoS metrics and T&E objectives?
- Systems Changes: Are expected cumulative impacts of systems changes on SoS performance the same as SoS performance objectives?
- End-to-End Testing: How do you test the contribution of a system to the end-to-end SoS performance in the absence of other SoS elements critical to the SoS results? What if the constituent systems are all implemented to their specification but the overall SoS expected changes cannot be verified?

The NDIA have been working on how to address these issues, and the solutions relevant to the Australian circumstances have been assimilated into Section 7.3.

## 6.2 SoS Questions to Answer

The following is a list of questions posed by Hess (2010) that relate to SoS T&E:

- How much testing is enough?
- How long will testing take?
- How much will it cost?
- How do I test effectively given the compressed schedule of a "Rapid Acquisition" program?
- How do I measure the quality of my tests?
- What are the most valuable tests for my system?
- How should I prioritize my tests?
- How do I make sure my tests are representative of the operational environment?
- How do I get more knowledge for my dollar?
- What are the unique challenges in testing Systems-of-Systems (SoS)?
- How do I test a SoS without explicit requirements?
- How does my system affect the SoS in which it operates?
- What are the most valuable tests for my SoS?

Additional questions that might be considered also include:

- How can the relevant SoS T&E requirements be addressed within the T&E program for each of the constituent projects?
- What T&E can be undertaken within a constituent project to access its potential contribution of the larger SoS(s)?
- How will T&E of the SoS shape future phases of the constituent projects?

Given the challenges inherent in SoS T&E listed above, the answers to these questions will need to be found both in the overall framework for SoS T&E and through formation of SoS T&E practitioners who can cope with the inevitable compromises and incompleteness of SoS T&E.

## 6.3 SoS T&E Framework

Dahmann (2012) and Dahmann et al (2010) provide a progress report on the work underway by the NDIA SE Division SoS SE and T&E Committees on best practices in SoS T&E. They state that it is important to note that SoS T&E is fundamentally different in goals, character, and intent from system-acquisition T&E that seeks to inform acceptance and deployment decisions.

Dahmann et al. (2010), Dahmann and Heilmann (2012), and Dahmann (2012) raise several important points to consider when discussing SoSE and T&E. Firstly, the point is made that SoSE and T&E is done as an integrated part of the SoS evolution process and SoSE and SoS T&E share key common elements. In that context, SoS T&E needs to be focussed on SoS operational performance. Secondly, it is essentially impossible to test a substantial SoS, so other means of evaluating the operational effectiveness and suitability of SoS need to take a larger place on the palette of T&E approaches. These would include:

- Modelling and simulation
- Analysis
- Experimentation
- Exercises
- Operations
- Incremental testing

The work of Dahmann, Wilson and colleagues invokes the goal of T&E from the US DoD Acquisition Guidebook: “The overall goal of T&E is to reduce risk by providing crucial information to decision makers” and proposes a T&E approach that reflects this and is characterised by the following core ideas:

- Integrate T&E with SE throughout the evolution of an SoS;
- Focus T&E on risk, both in the planning of the SoS and in its implementation;
- Employ a variety of sources of evidence including prior T&E results, data from analysis, and SoS test events as needed;
- Radically change how we look at testing given the growing prevalence of SoS:

  - Concepts of Developmental Test (DT) and Operational Test (OT) don't really fit,
  - Inefficient to address systems in operational SoS environment on a system-by-system basis (OT today),
  - Continue to test individual systems to assess whether we have developed what we asked for, and
  - Create a new approach to OT through cross-systems support for testing integrated capabilities[2];
- Characterize SoS T&E as continuous improvement, document the approach and share with the community;
- The SoSE Team needs to work very closely with the constituent system SPOs in order to facilitate a workable SoS solution;
- Establish incentives of constituent systems to collaborate and achieve SoS performance objectives; and
- In later iterations, map SoS capabilities and performance objectives to constituent systems (under configuration control).

The following sections discuss the SoS T&E activities that would be conducted in each stage of the Wave Model. It should be noted that we are proposing that the Agreement between the SoS Team and the constituent system SPOs be expanded to include the high-level technical performance and behaviour that the constituent system is to provide to the SoS. This needs to shape the constituent system T&E program to access the capability of the constituent system to contribute to the SoS in an operational context.

Furthermore, it is important to appreciate SoSE and SoS T&E are inherently evolutionary activities that progressively shape the SoS towards its goals. Each iteration of the wave model provides an opportunity to shape the constituent systems to contribute more effectively to SoS operational performance. It needs to be understood that it may take more than one cycle to shape some constituent systems depending on the synchronisation of the individual SPO capability cycles with the SoS wave.

## 6.4 SoS T&E Activities

### 6.4.1 SoS Initiation

Dahmann and Heilmann (2012) assert that Capability Objectives and the SoS CONOPS provide the foundation for T&E, providing SoS high-level capability measures of effectiveness and operational context. These are first recorded in this stage and, together with the associated mission threads and military tasks, these form the inputs for structuring T&E activities and for teasing out critical operational issues and T&E measures such as SoS measures of effectiveness, measures of suitability, and measures of performance.

At this stage, the constituent system information is gathered and T&E results from constituent system programs are scrutinised for information that will impact on the SoS measures.

[2] This is already being done in Australia as demonstrated through the Land 200 trials that treated a collection of C4I projects (Land 75, Land 125, JP 2072) as an integrated SoS.

SoS T&E planning commences at this stage and is refined during the SoS analysis stage. This should include identifying opportunities to incorporate relevant SoS T&E elements in constituent SPOs.

### 6.4.2 SoS Analysis

The SoS Capability and Performance Objectives that are updated during SoS Analysis provide the foundation for SoS T&E. Acknowledged SoS comprise existing, fielded systems, and hence understanding current and potential SoS performance requires an understanding and assessment of the T&E results of constituent systems, the existing SoS plus a forward vision and concept for the SoS. Dahmann (2012) states that systematic development and analysis of this data is core to SoS analysis and since SoS typically brings systems together in new ways, there is a need to obtain more data. This data may be from specific testing, demonstrations, exercises, modelling and simulation, experimentation or analysis. This will include analysis of the future force operational effectiveness using combinations of wargaming, modelling and simulation.

The analysis should identify major changes to the existing SoS and its constituent systems and how they may result in change to the SoS, its operation and performance. Significant changes to the technologies of key constituent systems (often in combination such as information systems, networking and sensors) may result in major changes to the scope of the SoS capability, the SoS business processes. These changes may require significant adjustment in SoS T&E.

### 6.4.3 SoS Architecture Development and Evolution

Dahmann (2012) and Dahmann and Heilmann (2012) state that T&E data on the attributes and performance of constituent systems is key to the identification and analysis of architecture approaches. Furthermore, Dahmann states that because the components of the SoS typically include existing systems, T&E methods and tools can contribute to the assessment of alternative architectures through the application of various approaches including live, virtual and constructive environments to assess alternatives against desired architecture objectives.

In addition, knowledge about T&E considerations of the constituent systems test and certification requirements can inform architectural options. For example, if rapid changes are required, then the T&E community can help designers understand which constituent systems would have short-enough time test and certification lead times to contribute to the solution.

Conversely, systems and SoS architectures can be used to shape and inform the design of the SoS T&E. In addition, the SoS architectures can be used to identify T&E to access the performance of the constituent systems and the ability to contribute to the SoS capability. These constituent system T&E insights can in turn be used to shape the T&E to be undertaken within the individual SPOs to enable them to, in part, assess the potential of the systems to contribute to the SoS.

### 6.4.4 SoS Update Planning

Dahmann (2012) states that T&E planning is a core part of the planning for an update, and, given the obstacles to conducting full SoS testing with each change in a constituent system within the SoS, this step is critical in identifying areas of risk that warrant T&E attention. During this stage, expected changes in constituent systems are identified: those changes planned by the constituent system SPO for their own purposes, and those being planned to address SoS needs. The T&E people assess the potential impact of these changes using the architecture as the technical framework to determine how the planned change will affect other constituent systems in the SoS given the CONOPS and system dependencies.

Where risks are identified, the SoS T&E people will need to determine how these will be assessed and how they can be mitigated. It should be noted that changes with no impact on other parts of the SoS (e.g., improved quality of sensor feeds but no change in format, interfaces, volume, etc.) may not need SoS attention beyond T&E at the system level.

### 6.4.5 SoS Update Implementation

Dahmann (2012) asserts that T&E is a key part of implementation for both SOS and constituent systems. Systems making updates conduct T&E at the system level in the normal way. Based on the assessment of impacts of changes on other parts of the SoS, added T&E elements have been included in the system test plans. SoS T&E includes monitoring the implementation of the planned system testing, conducting added testing to address SoS risks, evaluating the results, and recommending changes in plans as needed. SoS capability results are identified (both planned and unplanned).

T&E questions surrounding the SoS implementation step include the following:

- What is the operational performance of the SoS at this increment?
- Does performance meet expectations for this increment?
- What are the causes for any shortfall or improved performance relative to the earlier SoS iteration and the expected SoS performance?
- What are the potential impacts of any shortfall or differences on the next increment?
- What are the risks?
- What evidence is there that these changes will need to be regression tested in the next increment?

The answers to these questions become the basis for capabilities and limitations information provided to end users and serve as feedback to the SE and T&E teams for the SoS and systems toward continued evolution of the SoS.

# 7. Metrics for Land Capability SoSE Success

One of the challenges associated with determining the effectiveness of any SE effort is that it is very difficult to conduct a set of controlled experiments that can yield statistically significant results as would be done in many areas of research endeavour such as medicine.

The preferred approach to date is to conduct case study research. Cook (2000) addressed the problem of how best to achieve SE success through a literature survey that drew on substantial published experience of SE lessons learned. Honour (2004, 2006, 2010a & b), in contrast, formulated a pioneering research approach that interpreted the extent to which good SE practices have been followed in a project and the quality of those practices in order to establish the value of systems engineering and the return on investment for systems engineering. Honour's methodology involves data collection through confidential interviews with leading systems engineers and subsequent statistical analysis of the data set. Survey work by Elm et al (2008) supports Honour's results and further surveys are being conducted to enhance the results. These approaches have succeeded on the basis of having a statistically significant data set.

Given the lack of such a data set, perhaps the most promising technique would be to benchmark the land SoS challenge against similar efforts overseas suitably normalised for size and level of SoS effort relative to estimated effort for good practice (see Lane, 2009). Another useful approach would be to compare the evolving land SoS practice against the patterns for SE success developed by Rebovich and De Rosa (2011). A third approach would be to try to identify SoS leading indicators from the work of Roedler et al (2010).

Guckert (2012) describes the US Army SoSE Organisation and a recent workshop surfaced a list of metrics that apply to that organisation. However, stakeholder comments suggest that the percentage-based metrics proposed were not very informative and trends would be more useful, costs should be included, measures for suitability and effectiveness need to be considered, as should metrics related to stakeholder engagement. It was also suggested that a more holistic view of SoSE success could be achieved through the use of Balanced Scorecard methods. The final version of these metrics could well be informative for the Australian Army circumstances.

Agreement between the constituent projects and with the SoSE team have been proposed in this report as a key component of achieving effective SoSE. A mathematical formalism could then be established to assess the overall 'health' of the SoSE process based on the measures relating to the SoS agreement framework.

Note that SoS analysis and T&E will identify issues, gaps and risk before and after each SoSE wave. This information might be used as a method to monitor SoSE performance.

Ultimately, the success of SoSE will be judged in terms of the achieved SoS capability performance versus the cost of undertaking SoSE. This could be assessed in a manner analogous to Honour's approach that established, through research covering over 50 projects, that there is a substantial return on investment in performing systems engineering. A key

return on investment is likely to be a transfer of the SoS integration risks from the operational level (i.e. the warfighters), where they have been traditionally addressed, to the capability development domain.

# 8. Conclusion

This report set out to provide advice on:

1. Capability/SoS project requirements development and specification; and

2. Test and Evaluation (T&E) process for capability/SoS integration to ensure that the delivered constituent systems will be effective components of land force capability.

It quickly became apparent during the research program that, for the advice to have meaning to potential SoS stakeholders in Defence, it would be necessary to place it within the context of a SoSE approach. This reports draws on significant international literature and personal communications with leading practitioners to present an approach which is considered "culturally feasible", to use Checkland's Soft System Methodology Language (Checkland & Scholes, 1999), in the Australian Defence context. To that end, this report has provided an outline of an overarching approach that has the potential to address the current and forthcoming land SoS integration challenge in a way that is very cost effective and sensitive to the extant cultural, financial and organisational realities in which the approach would be employed.

The approach seeks to encourage constituent system SPOs to embrace the land SoS vision and keep it front-of-mind in the delivery and sustainment of the constituent systems that will provide the equipment that will comprise the SoS. It will require some modest additional roles and responsibilities in each SPO and a small SoS Team to be successful.

In response to the first question, we show how capability requirements for the SoS are elicited and how the SoSE analysis stage identifies how these can be mapped onto constituent systems in the form of high-level service definitions (analogous to service contracts). In the first iteration, the SoS Team will have little opportunity in the short term to change constituent systems requirements or project scope, and hence the approach chosen to interface to the SPOs is to establish agreements that embody the service definitions. It is these service and interface definitions that are tracked by both parties and form the basis for guiding the evolution of the SoS.

In response to the second question, we assert that SoS T&E is fundamentally different in goals, character, and intent from system-acquisition T&E that seeks to inform acceptance and deployment decisions. SoS T&E is focussed more on the operational performance of the SoS because it is deemed impractical to conduct comprehensive testing of an evolving SoS. Thus SoS T&E activities focus on the impacts that constituent systems iterations will make on the SoS performance and behaviour outcomes. As such, it involves far greater use of modelling, simulation and analysis than project T&E, and the conceptualisation of training, exercises, and operations as T&E opportunities. Nonetheless, the SoS T&E staff would monitor constituent system project progress to evaluate whether the service provision clauses of the agreements will be achieved.

A final point is that SoSE is quite different from project SE, and SoS T&E is fundamentally different from project-based T&E. Both disciplines will require highly capable and adaptable people that display the appropriate mind-set, attitude and aptitude needed for SoS success. Identifying and nurturing the development of these people is an important subject for further consideration.

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# Annex A: Definition of Terms

## A.1 Introduction

There are many definitions for SoSE and what it is often called in Australia *Systems of Systems Integration*. As part of the RPDE QL 62 task, the team[3] that included the first author of this report was asked to produce a list of definitions in order to ensure a common language and to enable the team to communication effectively with stakeholders, we were asked to define the following terms.

- System of Systems (SoS),
- System of Systems Integration (SoSI); and
- High End Systems Integration (HESI)

The US definition of SoSE is also included in the background material.

The definitions are based on existing work abstracted in Section 5. They were discussed at the Industry Workshop held in Brisbane on 24-25 August 2010 with a group of over 30 RPDE representatives from defence industry, the Department of Defence, and academia (Jacapino 2010). The definitions were then refined with reference to the latest literature to form the first published version that was used to support the interview process where they were exposed, with no adverse comment, to many Defence senior executives. The definitions were exposed to a second workshop on 2 December 2010 and the final definitions that appear below incorporate a few minor changes that arose from the salient suggestions captured at that event.

The definitions given below are intended for use in defence capability development, acquisition, supplier, and operational contexts.

## A.2 Definition of System of Systems

*In the Australian Defence context, a system of systems (SoS) is a large, complex system that exhibits the following two essential characteristics that distinguish it from a large, monolithic system:*

- ***Operational independence of component systems*** *(Component systems are independent and useful in their own right.)*
- ***Managerial independence of the component systems*** *(Component systems are separately acquired and integrated but maintain a continuing operational existence independent of the SoS. NB: A component system could be a constituent part of one or more SoS.)*

*SoS usually exhibit the following additional properties:*

---

[3] The team included S Cook, R Jeffery, B Madley, T Stevenson, D Williamson, S Soutberg, A Pitman and A Jacapino.

- ***Evolutionary development*** *(SoS do not arrive full formed. Development is evolutionary with functions and purposes added, removed or modified with experience.)*
- ***Emergent behaviour*** *(A SoS performs functions and carries out purposes that do not wholly reside in any component system.)*
- ***Geographic distribution*** *(The geographic extent of the component systems is often large thus SoS, most often, can readily exchange only information and not substantial quantities of mass or energy.)*

*SoS are systems at a level of hierarchy beyond what we normally consider in a single Major Capital Equipment (MCE) project. In this context, MCE projects give rise to component systems whereas SoS come into being through the action of integrating multiple systems that were not necessarily intended to connect together.*

## A.3 Definition of High-End Systems Integration

Systems integration can have several meanings as outlined in this missive at 5.2. It can be a noun that labels a type of business, an adjective that qualifies a type of project, or a noun that relates to the activity of doing the integration phase of any engineering project or of doing a whole systems integration project. It is the latter definition that is proffered here.

*High-End Systems Integration is a systems engineering approach employed to realise large, complex, systems (of the scale and complexity tackled by ACAT 1 or the more challenging ACAT II Major Capital Equipment projects) that places the major emphasis on utilising mostly pre-existing components and focuses the engineering, and management of such engineering, on the inherent complexity of the interfaces between those components.*

## A.4 Definition of System of Systems Integration

The degree of difficulty in defining this term comes from the fact that there are at least four types of systems of systems as described in Section 5.1 and that many SoS are integrated upon deployment. A better term to use might be *systems of systems engineering* which is well understood, enjoys a wide usage, and for which there are a number of guidebooks (USN 2006a & b). It is also important to understand that there are at least two important perspectives to consider on SoS integration. The first is the enterprise perspective taken by Defence, or similar customer and operating organisations such as the FAA, that is concerned with integrating (military) capabilities across all fundamental inputs to capability as described by the NCW Integration and Implementation Strategy (Defence 2010). NCWIIS refers to this as *capability integration* and terms such as *capability engineering* (INCOSE UK 2010), *force-level systems engineering, enterprise systems engineering* are often applied to this class of activity. The second perspective is the supplier's view of systems-of-systems that, while aware of the broader enterprise-level integration concerns, is focussed on the technical challenges of integrating disparate systems and the impacts SoS considerations may have on the component systems they are supplying and sustaining. The following definition attempts to cover both perspectives:

*Systems of Systems Integration (SoSI) is a systems engineering approach to planning, analysing, organizing, and integrating the capabilities of a mix of existing and/or new systems into one or more*

*system-of-systems capabilities that are greater than the sum of the capabilities of the constituent parts. SoSI emphasizes the process of discovering, developing, and implementing standards that promote interoperability among systems developed via different sponsorship and management processes.*

*The framework for achieving SoSI within the Australian Department of Defence is described in the NCW Integration and Implementation Strategy that outlines an enterprise systems engineering approach to achieving capability integration.*

*It is recognised that SoSI requires the integration of defence enterprise elements and, as such, transcends technical concerns and embraces all Fundamental Inputs to Capability.*

## A.5 Background Material

### A.5.1 Background for systems of systems definition

The definition provided draws on Maier's original definition of systems of systems (Maier 1998):

> "Five principal characteristics are useful in distinguishing very large and complex but monolithic systems from true systems-of-systems.
>
> 1. Operational Independence of the Elements: If the system-of-systems is disassembled into its component systems the component systems must be able to usefully operate independently. The system-of-systems is composed of systems which are independent and useful in their own right.
>
> 2. Managerial Independence of the Elements: The component systems not only can operate independently, they do operate independently. The component systems are separately acquired and integrated but maintain a continuing operational existence independent of the system-of-systems.
>
> 3. Evolutionary Development: The system-of-systems does not appear fully formed. Its development and existence is evolutionary with functions and purposes added, removed, and modified with experience.
>
> 4. Emergent Behavior: The system performs functions and carries out purposes that do not reside in any component system. These behaviors are emergent properties of the entire system-of-systems and cannot be localized to any component system. The principal purposes of the systems-of-systems are fulfilled by these behaviors.
>
> 5. Geographic Distribution: The geographic extent of the component systems is large. Large is a nebulous and relative concept as communication capabilities increase, but at a minimum it means that the components can readily exchange only information and not substantial quantities of mass or energy."

Furthermore, Maier (1998) seeks to identify those characteristics that distinguish a system of systems from a large, complex monolithic system. He concludes that operational and managerial independence, i.e. the first two characteristics, are sufficient for this purpose and

the remaining three, while usefully descriptive, are not able to assist in distinguishing the two types of system.

It is important to be aware that SoS can take different forms and as such different approaches are needed to guide their evolution and operation. The following excerpt summarises this for defence applications (OSD 2008):

> "In DoD and elsewhere, SoS can take different forms. Based on a recognized taxonomy of SoS, there are four types of SoS which are found in the DoD today [Maier,1998; Dahmann, 2008]. These are:
>
> **Virtual.** Virtual SoS lack a central management authority and a centrally agreed upon purpose for the system-of-systems. Large-scale behavior emerges—and may be desirable—but this type of SoS must rely upon relatively invisible mechanisms to maintain it.
>
> **Collaborative**. In collaborative SoS the component systems interact more or less voluntarily to fulfill agreed upon central purposes. The Internet is a collaborative system. The Internet Engineering Task Force works out standards but has no power to enforce them. The central players collectively decide how to provide or deny service, thereby providing some means of enforcing and maintaining standards.
>
> **Acknowledged.** Acknowledged SoS have recognized objectives, a designated manager, and resources for the SoS; however, the constituent systems retain their independent ownership, objectives, funding, and development and sustainment approaches. Changes in the systems are based on collaboration between the SoS and the system.
>
> **Directed.** Directed SoS are those in which the integrated system-of-systems is built and managed to fulfill specific purposes. It is centrally managed during long-term operation to continue to fulfill those purposes as well as any new ones the system owners might wish to address. The component systems maintain an ability to operate independently, but their normal operational mode is subordinated to the central managed purpose.
>
> This characterization offers a framework for understanding SoS in the DoD today. With the advent of networks and increased efforts to link systems for information sharing across the battle space, most systems are part of virtual SoS. DoD net-centric policies and strategies have attempted to provide crosscutting approaches to fostering information sharing in the absence of explicit shared objectives or management. (See section 1.5.2)
>
> As users and systems owners understand their interdependencies, there are increasing examples of collaborative SoS where representatives of systems choose to work together for their mutual benefit. Communities of interest (COI), where volunteers come together to develop ways for shared interests to be addressed collaboratively by participants working under their current structures, are a good example.
>
> In a few cases, most notably Future Combat Systems, a common objective has driven the development of the constituent systems from the outset. Systems in this category therefore constitute a directed SoS.
>
> In the DoD today we see a growing number of acknowledged SoS. Like directed SoS, acknowledged SoS have recognized authorities and resources at the SoS level. However,

> because an acknowledged SoS comprises systems that maintain independent objectives, management, and resources, along with independent development processes, these SoS are largely collaborative in practice. For systems in these SoS, in particular, their normal operational mode is not subordinated to the central managed purpose—a distinct feature of a directed SoS. Because defense acquisition and funding are still largely platform focused, many SoS do not have authority over the systems, and they typically try to address SoS objectives by leveraging the developments of the systems, which are normally more long-standing and better supported than the SoS. Consequently, acknowledged SoS, like directed SoS, have objectives, management, and funding without authority over the constituent systems. Like collaborative SoS, changes in systems to meet SoS needs are based on agreement and collaboration, not top-down authority from the SoS manager."

SoS are often differentiated from large monolithic systems by comparison illustrations and tables, see Figure A1 and Table A1 below.

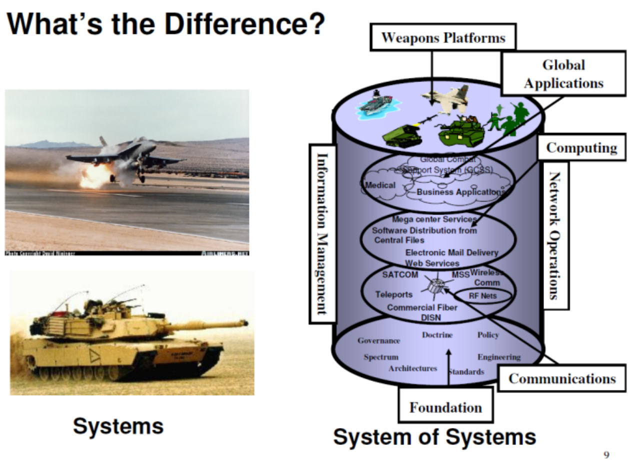


*Figure A1 Illustrative difference between monolithic systems and SoS (Kaplan 2007)*

*Table A1 Comparison of conventional military systems and systems of systems (Cook 2001)*

| System Attribute | Simple Military Systems | Military System-of-Systems |
|---|---|---|
| Example | Artillery piece | Combined peace-keeping force |
| System characteristics | Mechanistic but human directed. | Socio-technical; involves people, organisations, doctrine, equipment … |
| Number of system elements | Small | Large |
| Interaction between elements | Few | Many |
| Attributes of Elements | Predetermined | Not predetermined |
| Interaction between elements | Highly organised | Loosely organised; but interfaces critical |
| Behaviour | Governed by well-defined laws | Probabilistic |
| Evolution | Does not evolve | Evolves over time |
| Nature of sub-systems | Do not pursue their own goals | Are purposeful and generate their own goals |
| Interaction with environment | Little | Interacts strongly |
| **System Practice** | | |
| Requirements elicitation | Straightforward, use good systems engineering practice | Problematical because of evolutionary nature and unanticipated needs. |
| Creation methodology | One or a few specific acquisition actions | Either evolve through multiple acquisition or synthesised and adapted from existing inventory to meet an unanticipated requirement |
| Key systems philosophy | Closed | Open |
| Key design philosophy | Controlled process | Adaptability and flexibility |

Enterprises are often included in the class of SoS and there is a significant literature on Enterprise Engineering (BKCASE 2010) that describes how conventional systems engineering principals can be extended and applied to enterprises. Martin (2010), however, makes a distinction between enterprises and SoS and consequently Enterprise Systems Engineering (ESE) and SoS Systems Engineering (SoS SE). This is shown pictorially below in Figure A2 that shows that SoS can span enterprises and this view is helpful when one considers SoS SE from a supplier perspective. The SoS SE perspective has a greater focus on technical issues and interoperability than it does certain of the enterprise extensions to conventional SE practice.

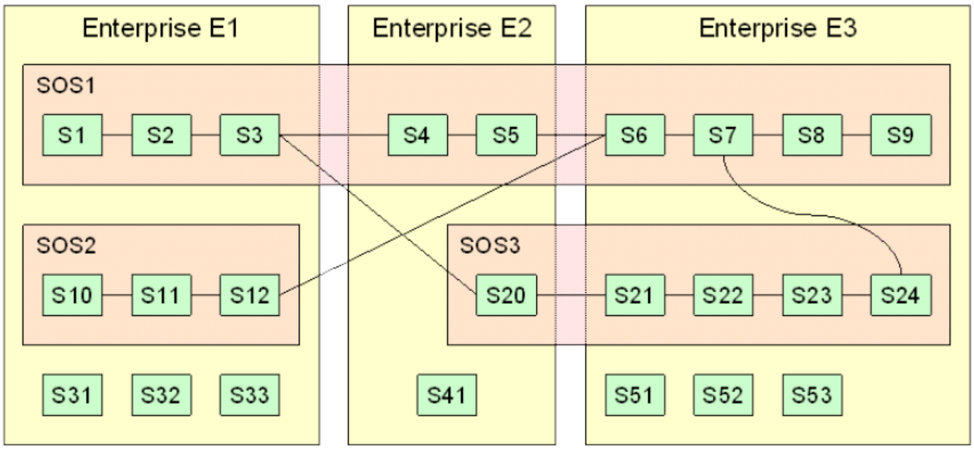


*Figure A2. Relationship between an Enterprise and a SoSs (from Martin, 2010)*

### A.5.2 Background for High-End Systems Integration Definition

'High-end systems integration' is a term had little currency before the advent of the Priority Industry Capabilities. It is assumed that 'high-end' refers to the complexity and scale of the systems of interest in a Major Capital Equipment project. It is thus reasonable to assume that high-end systems integration is encountered in ACAT 1 systems integration projects and perhaps some ACAT 2 projects. See Table A2 for a definition of ACAT levels.

*Table A2. Definition of ACAT levels from the Defence Capability Plan (Defence 2009b)*

| |
|---|
| The ACAT framework is based on four Acquisition Categories that provide a graduated scale from the most demanding and complex projects to those that are less so. The largest, most demanding and complex projects are categorised as ACAT I and ACAT II, and the less demanding projects are categorised ACAT III and ACAT IV. The specific description of each level is as follows: |
| > ACAT I projects are major capital equipment acquisitions that are normally the ADF's most strategically significant. They are characterised by extensive project and schedule management complexity and very high level of technical difficulty, operating, support and commercial arrangements. |
| > ACAT II projects are major capital equipment acquisitions that are strategically significant to the ADF. They are characterised by significant project and schedule management complexity and high levels of technical difficulty, operating, support arrangements and commercial arrangements. |
| > ACAT III projects are major or minor capital equipment acquisitions that have a moderate strategic significance to the ADF. They are characterised by the application of traditional project and schedule management techniques and moderate levels of technical difficulty, operating, support arrangements and commercial arrangements. |
| > ACAT IV projects are major or minor capital equipment acquisitions that have a lower level of strategic significance to the ADF. They are characterised by traditional project and schedule management requirements and lower levels of technical difficulty, operating, support arrangements and commercial arrangements. |

### A.5.3 Background Information on the Definition of SoS Integration

Some helpful definitions follow:

> "System-of-Systems Engineering (SoSE) is defined as: *The process of planning, analyzing, organizing, and integrating the capabilities of a mix of existing and new systems into a system-of-systems capability that is greater than the sum of the capabilities of the constituent parts. This process emphasizes the process of discovering, developing, and implementing standards that promote interoperability among systems developed via different sponsorship, management, and primary acquisition processes"* (USAF 2005).
>
> "… we shall define *capability engineering* as a way of conducting capability planning, architectural design, and management across a number of projects that draws on systems engineering principles for its philosophical basis" (Cook & Mun, 2006).
>
> "The Naval "Systems of Systems" Systems Engineering Guidebook, Volume 1, Version 1.2 (originally issued as the Naval Capabilities Evolution Process Guidebook, Volume 1) describes a comprehensive process for applying system-engineering principles that combine the capability focus of JCIDS with the evolutionary acquisition strategy of the Defense Acquisition System to evolve to a networked systems environment. This Volume II of the Guidebook provides an initial set of best practices that can be applied to implement the recommended "systems of systems" systems engineering process. The intent is that this initial set will be significantly augmented by recommended best practices for capability-based acquisition and systems engineering from across the Naval acquisition community. In this regard, your best practices are solicited and requested to be submitted to the ASN (RD&A) Office of the Chief Engineer" (Defence 2010).

> "SoS SE is defined by the US OSD as a set of SE activities that need to be performed at the portfolio level" (Maier 1998).

Enterprise SE seeks to lift conventional product-based SE to the enterprise level through broadening the scope of traditional SE process and work products and by additional processes that cover:

- Strategic technical planning
- Enterprise architecture
- Capabilities-based planning analysis
- Technology planning
- Enterprise analysis

The INCOSE UK Capability Working Group Perspectives Analysis Sub-Group examined capability engineering from the perspective of eight worldviews (INCOSE UK 2010) encountered in the UK on what comprises capability engineering. This approach offers the advantage of not needing to come to a compromise definition and of being able to surface a broad range of perspectives.

Figure A3, extracted from the reference illustrates how the eight worldviews map onto five perspectives and Hitchins' five layers of systems engineering (Hitchins 2003).

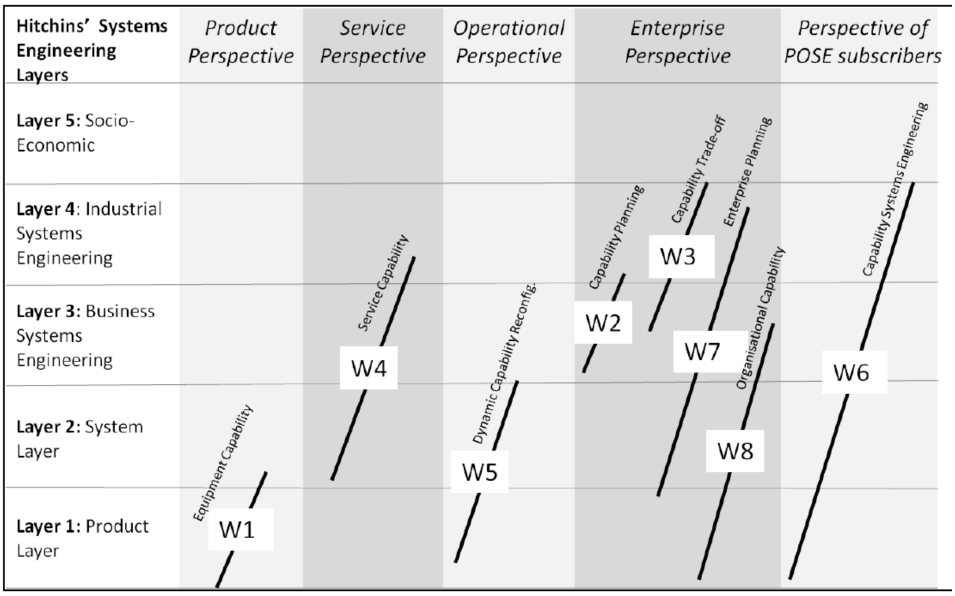


*Figure A3. Weltanschauungen (worldviews) of capability engineering as related to the Hitchins' Five Layer Model of systems engineering*

As one would expect, different stakeholders hold different worldviews. The NCWIIS takes an enterprise perspective and an operational perspective as these perspectives reflect the role of members of the Department of Defence. Industry on the other hand could be expected to take a service perspective, where they see capability engineering as providing a service to a customer, and

a product perspective where they need to consider how SoS imperatives map onto the product systems they are delivering and sustaining.

This figure is interesting in that it helps explain the breadth of positions of what constitutes capability engineering. It is also useful to highlight the perspective of Plain Old Systems Engineering (POSE) subscribers who believe that capability engineering can be encompassed by the broad church of systems engineering described by those such as Hitchins and Hall who assert that good systems engineering concepts can inform systems engineering activities at all levels of complexity. Indeed the authors cited described SoS approaches around twenty years ago.

In formulating the definition of SoSI, an attempt was made to incorporate both the supplier view and the multiple Defence enterprise views as articulated by the NCWIIS.

# Annex B: SoSE Artefacts for Land Force Capability

This section describes each of the SoS SE artefacts discussed e. These definitions are largely extracted from Dahmann et al (2010) and supplemented from Dahmann (2012) but have been modified, as needed, to suit the Australian Land Force Capability Context. The descriptions also include a discussion of how each artefact is used in the SoS SE process.

It should be noted that constituent systems SPOs implement SE for their systems and create artefacts to support their processes. For those interested, Dahmann et al (2010) provide a useful comparison between SoS SE artefacts and constituent system artefacts. In general, SoS artefacts address comparable issues but with a broader focus across the SoS and tend to take a less prescriptive tone. In most cases, constituent system owners and the engineering team with the SPO retain responsibility for their systems even when they are part of a SoS. There is no intention to replicate information available for the systems in SoS artefacts but rather to point to that information retained by systems as it impacts the SoS.

**SoS Capability Objectives** are a statement of top level objectives for the SoS. They describe the capabilities needed by the user, ideally based on some definitive or authoritative materials (e.g., White Paper, Defence Capability Planning Guidance, strategies or Australian Capability Context Scenarios). They are used by the SoS Team and stakeholders as the foundation for SoS requirements, metrics, etc. The capability objectives provide a basis for translating operational needs into high level requirements, assessing performance to capability objectives, and developing an architecture and solution options.

The **SoS CONOPS** describes how the functionality of the constituent systems in the SoS will be employed in an operational setting. The CONOPS (CONcept of OPerationS) is developed by the prospective operational users and with active participation from the SoS Team to describe the way users plan to operate and use constituent systems to achieve the objectives, as influenced by the various environments and conditions anticipated. The CONOPS is developed in parallel with the capability objectives and as the capability objectives evolve, the CONOPS should evolve in detail, as well. The SoS Team and the SPOs use the CONOPS to define the SoS requirements space, to identify aspects of constituent systems which could impact the SoS design, and to select performance metrics and test environments.

**Systems Information** is accessed and organized by the SoSE Team and is used as the basis for trades as the SoS evolves. This is information about constituent systems that impacts SoS capability objectives and includes both programmatic and technical aspects of the constituent systems relevant to the SoS. The information comes from many stakeholder groups including the design and sustainment staff in the SPOs, the operators, and the contractors supporting the system. It is important that the responsibility for producing the information and keeping up to date be allocated to the SPOs because the SoSE Team will never have the resources to elicit this information and configuration management it. It also must fall to the SPO to alert the SoS Team whenever there are changes in the constituent system that are liable to impact the SoS. The Agreements (discussed later) need to include this service from the SPOs to the SoS Team. This information assists the SoS Team to understand the components of the SoS,

including technical, organizational, fiscal, and planning perspectives. The information provides the basis for developing and evolving the SoS architecture, monitoring and assessing changes to both the SoS and individual systems, and developing SoS capability solution options.

The **SoS Requirements Space** bounds the first-order SoS user needs (including operational tasks and missions) and defines the functions required to provide the capability across the range of user environments likely to be encountered. It should be noted that this artefact is a 'requirements space' versus a set of 'requirements', because in a SoS, 'requirements' are taken on by the constituent systems to meet the SoS. The requirements space includes both the SoS Capability Backlog and Problem Reports. It is developed by the SoSE Team in liaison with constituent system SE teams and with strong engagement with SoS and constituent system operational communities. It is used by the SoSE Team and constituent system SE teams to: determine information needed to understand systems and relationships, compare performance to capability objectives, develop an SoS architecture, identify areas to be addressed in an increment(s), identify solution options, develop a plan for SoS increment(s), and develop a plan to test and evaluate the changes.

**SoS Performance Measures and Methods** provide the basis for assessing overall performance of the SoS and planning for 'continuous SoS improvement'. These performance measures and methods are traceable to the capability objectives established for the SoS. They are created by the SoSE Team and the constituent system SE teams together with the test and evaluation (T&E) community to assess status and progress in meeting SoS capability objectives and are used to structure events to generate the data needed.

**SoS Performance Data**, along with data on unanticipated factors observed during performance analysis, are gathered from different environments by the SoSE Team and the T&E teams and operators to assess progress toward achieving SoS capability objectives. These data are used by SoS management and SE teams to assess the impact of changes and to identify areas needing more attention (new gaps/requirements). The data also provide feedback on architecture implementation variability; factors impacting capability; and additional capability needs based on operational user experience. The aggregate feedback serves as a basis for addressing requirements and orchestrating SoS upgrades.

**SoS SE Planning Elements** provide the structure and process outline for SE for the SoS much as a System Engineering Plan (SEP) does for an acquisition program. Key elements include (1) battle rhythm or pacing of SoS upgrades, (2) organisational structures and decision processes, and (3) technical reviews. These elements are developed and evolved by the SoSE Team in conjunction with the SE teams from key constituent systems. The elements provide the basic SE rules of engagement for the SoS and are used by the full range of participants in the SoS to understand the overall SoS SE process.

**SoS Risks and Mitigations** are addressed throughout the process. The SoSE Team works in collaboration with constituent system SE teams to capture the potential risks associated with SoS capabilities and mitigations for them. The status of risks and their mitigation are updated on a periodic or event-driven basis and tracked by the SoSE Team, constituent system SE teams, and SoS stakeholders to understand potential risks, issues, and obstacles to achieving

desired capabilities and to guide selections of alternative solutions. SoS risks often emanate from areas outside the SoS where changes may impact SoS objectives, particularly changes made in the constituent systems to meet user needs. Monitoring and addressing this type of risk is an important role for the SoSE Team.

The **SoS Master Plan** is an integrated plan that provides a top level view across multiple incremental upgrades to implement the SoS evolution strategy; it is the SoS analogue to a systems acquisition strategy. This plan is developed and evolved by the SoSE Team in collaboration with constituent system SE teams. The SoSE Team, constituent system SE teams, and SoS stakeholders use it to understand current status and plans of the SoS. Since this master plan looks across iterations of the SoS, it provides a mechanism for supporting trade-off decisions and adjusting priorities over time.

**Agreements** formalize roles and responsibilities of SoS participants at a broad level (e.g. Charter) as well as specific commitments of participants in a development increment. Because SoS cut across organizational boundaries, agreements are critical to SoSE SE success. The SoSE Team and constituent system SPOs (and contracting officers and commercial contractor representatives, as needed) define agreements among participants regarding organizational relationships, roles, and responsibilities, and to manage interactions of participants and other stakeholders.

**SoS Architecture** is the persistent technical framework for addressing the evolution of the SoS to meet user needs, and for addressing possible changes in constituent system functionality, performance, or interfaces. The architecture defines the way the systems work together and addresses the implementation of individual systems only when the functionality is key to crosscutting issues of the SoS (including shared data specifications or data models). It includes the constituent systems, key SoS functions supported by the systems, and relationships and dependencies as well as end-to-end functionality, data flow, and communications protocols. The SoSE Team defines the desired approach to organize existing and newly developed systems. The SoS Team and the constituent system SE teams use the architecture products as a framework for developing SoS solutions. It provides a shared representation of the SoS technical framework used to inform and document decisions and guide evolution of the SoS.

**SoS Technical Baselines** are developed for each increment of SoS development. These SoS baselines include a requirements baseline, an allocated baseline, and a product baseline for the SoS and reference the detailed system baselines maintained by the systems themselves. These are used to understand the current "as is" state of the SoS (product), monitor the SoS enhancements being currently developed for the next increment (allocated), and plan changes for future increments (functional/requirements).

**Technical Plans** are developed for each development increment and include plans for SoS implementation, integration, and test. SoS technical plans follow the principles for technical planning for systems, paying attention to defining critical event-driven reviews and risks throughout the process. The SoSE Team, the constituent system SPOs, and the T&E community use these plans to guide activities and document agreements on changes to be made in a SoS increment(s), to track implementation progress, and to identify changes/issues in implementation.

**Integrated Master Schedules** (IMS) are also created for each SoS development increment. They include the key points in the technical plans which need to be addressed in orchestrating SoS development. The IMS focuses on key SoSE activities and integration points and links to the detailed development schedules maintained by the systems for the update. In the IMS, the SoSE Team, in collaboration with constituent system SEs, identify key activities in SoS SE as well as common points (synchronization points, critical events) across elements of the SoS for an increment(s). The SoSE Team and constituent system SE teams use the IMS to monitor key points across elements of the SoS within the increment(s).

The **SoS Test and Evaluation Report** will take the form of an evaluation of the degree to which the SoS achieves the capability objectives and CONOPS at a particular point in time, either at a particular event such as the nominal completion of an iteration or at a calendar event such as the end of a particular year. It is widely recognised that it is impractical to test a SoS comprehensively in the same way that constituent systems are tested for compliance to a substantial requirement specification (Sage & Cuppan, 2001; Dahmann 2012; Kalawsky 2012). Thus SoS T&E has to performed on the basis of the SoS T&E plan and the emphasis will be on synthesising an evaluation of the SoS based on constituent systems test reports and models, SoS modelling and simulation, experimentation reports, operational reports and limited SoS testing.

| **DEFENCE SCIENCE AND TECHNOLOGY ORGANISATION DOCUMENT CONTROL DATA** | 1. PRIVACY MARKING/CAVEAT (OF DOCUMENT) |
|---|---|

| 2. TITLE | 3. SECURITY CLASSIFICATION (FOR UNCLASSIFIED REPORTS THAT ARE LIMITED RELEASE USE (L) NEXT TO DOCUMENT CLASSIFICATION) |
|---|---|
| A System-of-Systems Engineering Approach for Australian Land Force Capability Integration | Document (U)<br>Title (U)<br>Abstract (U) |
| 4. AUTHOR(S) | 5. CORPORATE AUTHOR |
| Stephen Cook, Stan Nowakowski and Mark Unewisse | DSTO Defence Science and Technology Organisation<br>PO Box 1500<br>Edinburgh South Australia 5111 Australia |

| 6a. DSTO NUMBER | 6b. AR NUMBER | 6c. TYPE OF REPORT | 7. DOCUMENT DATE |
|---|---|---|---|
| DSTO-TR-2743 | AR-015-388 | Technical Report | September 2012 |

| 8. FILE NUMBER | 9. TASK NUMBER | 10. TASK SPONSOR | 11. NO. OF PAGES | 12. NO. OF REFERENCES |
|---|---|---|---|---|
| 2012/1190984 | CDG 07/358 | DGLD | 65 | 83 |

| DSTO Publications Repository | 14. RELEASE AUTHORITY |
|---|---|
| http://dspace.dsto.defence.gov.au/dspace/ | Chief, Land Operations Division |

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System-of-Systems, Systems Engineering, Systems Integration, Land Force Capability

19. ABSTRACT
A system-of-systems engineering approach to suit the Australian land force capability integration challenge is developed drawing on the international body of knowledge. The approach proposed would require only quite modest resources. The nature of the activities and the artefacts to produce are defined, with a focus on SoS requirements engineering aspects and how these influence the resulting project- and SoS-level test and evaluation activities.